Advanced Lighting Guidelines

2001 Edition

Release Notes

Errata

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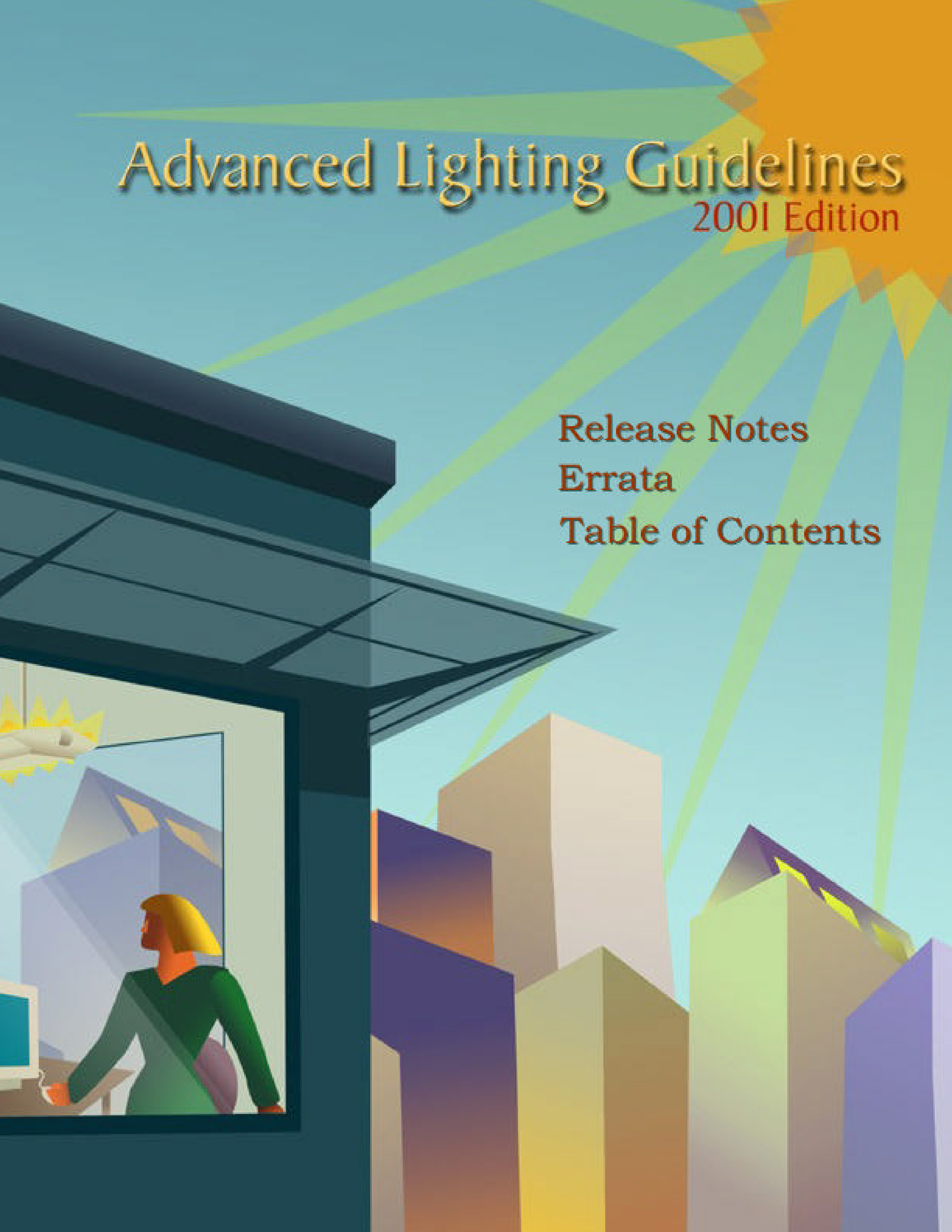

About New Building Institute, Inc.

The New Buildings Institute, Inc. (NBI) is a not-for-profit public benefits corporation helping to make buildings better for people and the environment through policy development, planning, and research.

NBI works with national, regional and state organizations, as well as with utilities, to advance our mission. We closely coordinate our building research, design guidelines and code projects so that all of the elements of good building design are integrated in the products and services we make available for use by energy efficiency programs throughout the United States. In addition to our formal projects, we often assume the role of "carrier" – bringing emerging good ideas and seasoned program models from one state or region to another.

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Release Notes

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Errata and Comments
Advanced Lighting Guidelines, 2001 Edition CD-ROM Release
July 20, 2001

Page #	Reference	Comment or correction
2-17	2.2.8	***References on EMF from Dr. Robert Levin, OSRAM SYLVANIA:*** 1) National Research Council (U.S.): Possible health effects of exposure to residential electric and magnetic fields, National Academy Press, Washington, DC, (1996). 2) JE Moulder: Power-frequency fields and cancer. Crit Rev Biomed Eng 26:1-116, 1998. 3) JE Moulder and KR Foster: Is there a link between exposure to power-frequency electric fields and cancer? IEEE Eng Med Biol 18(2):109-116, 1999. 4) National Research Council (U.S.): Research on Power-Frequency Fields Under the Energy Policy Act of 1992. Nation Academy Press, Washington, DC, 1999. 5) JE Moulder: The Electric and Magnetic Fields Research and Public Information Dissemination (EMF-RAPID) Program. Radiat Res 153:613-616,2000.
3-16	3.2.3	Para (1), 1st line add: "Lead may be found in most incandescent and <u>most</u> HID lamps...."
3-17	3.2.3	Para (1), last line, add: "....higher levels of mercury, <u>but in proportion to the light output</u>" Para (3) replace with: "Most States have now classified lamps which fail the TCLP test as "Universal Wastes". Generally this imposes much less stringent requirements on storage, transportation, and record keeping than a full hazardous waste classification. However, there are major variations state-by-state in lamp disposal requirements. The preferred method of disposal in most states is recycling. Contact information for each State, where current requirements can be obtained, is available on www.lamprecycle.org . California has recently adopted Universal Waste Emergency Rules, which are governed by the California Department of Toxic Substances Control. The current status should be checked, since the emergency rules are expected to be replaced with a final ruling in the near future.

Page #	Reference	Comment or correction
3-17	3.2.3	Para (4): change second sentence to: "A coal fired power plant may contribute several hundred times* more atmospheric mercury due to the energy use of an average fluorescent lamp compared to the amount of mercury that may be emitted when the lamp is properly recycled at the end of life"
6-26	6.5.1	Para (2) add note regarding dimming fluorescents: (Programmable-start ballasts are also suitable for dimming applications)
6-57	6.7	Para (2) add new sentence: The newest generation of LEDs is packaged in what is called a surface mount device (SMD).
6-57	6.7	Para (3) add parens to end of second sentence: (a "white" LED chip or semiconductor is via a blue emitting chip with a yellow emitting phosphor).
6-57	6.7	Para (4) add note: "Individual colors mix on the surface of projection or in the visual perception. There is no "white" output."
6-58	6.7.2	Para (1) add at end of 1st sentence: "or as time to half initial brightness."
7-10	Equation 7-2	Equation 7-2 includes the ballast factor (BF) as a component in calculating the lumen ratio. IESNA recognizes the BF as a non-recoverable light loss factor (LLF). If BF is used in the lumen ratio and as a LLF, calculations will result in an inaccurate measure because of double de-rating. The lighting professional should apply BF to the lumen ratio OR the LLF, but should not include it in both calculations.
7-15	7.3.2	Equation 7-2 in section 7.3.2 describes the ballast factor (BF) as a component in calculating the lumen ratio. If BF is used in the lumen ratio and as a LLF, calculations will result in an inaccurate measure because of double de-rating. The lighting professional should apply BF to the lumen ratio OR the LLF, but should not include it in both calculations.
7-40	Table 7-3	Information presented in the table on pages 7-40 through 7-45 represents general recommendations for common luminaries in various applications. The lighting professional must evaluate specific project criteria to determine the most suitable luminaire for the application. In some cases, a product may not be listed for a particular application, but may be appropriate for the application criteria. Likewise, if a product is listed for an application, it may not be suitable for all projects of that application type. This table will be updated in future editions of the Advanced Lighting Guidelines.

Page #	Reference	Comment or correction
7-48	Figure 7-32	Figure 7-32 illustrates lamp shielding ALONG the lamp axis. For advanced luminaries, typical shielding along the lamp axis is approximately 20 degrees. Lighting professionals should look for products with a louver shielding greater than 30 degrees ACROSS the lamp axis.
7-49	7.5.2	Replace first sentence with: "Luminaires for critical VDT applications often use a compound parabolic contour. This can be achieved using specially designed louvers in many narrow or wide luminaries."
7-66	7.5.5	Last bullet: "For ADA compliance, luminaries mounted between 27 in. and 80 in. above the finished floor should not project more than 4 in. from the wall."
7-75	7.5.8	Design and Control Considerations: "For ADA compliance, luminaries mounted between 27 in. and 80 in. above the finished floor should not project more than 4 in. from the wall."
7-102 to 7-106	7.9.3	The Application Correction Factor is not recognized by the IESNA Handbook or by the National Electrical Manufacturers Association (NEMA). The data presented in this section and Table 7-4 and Table 7-5 is based on tests that do not utilize current advanced technologies. Since the time this data was developed, new optical designs incorporate thermal management to maximize lamp performance. Most luminaire manufacturers provide photometric test reports using advanced lamp and ballast components, making the need for this adjustment unnecessary if ballast factor is accounted for in the Light Loss Factor (LLF) – see page 7-15. Using the Application Correction Factor with a luminaire designed to dissipate heat or with photometric reports utilizing advanced lamps and ballasts will result in an inaccurate assessment of the luminaire's performance. Luminaire input watts vary depending on the thermal characteristics of the luminaire type, the lamp and the ballast. Industry approved standard input watt data can be obtained from the NEMA Luminaire Efficacy Rating Standards (LE5, LE5A, and LE5B) at http://www.nema.org/products/div2/white_papers.html.
8-18	Figure 8-7	Change "Hunt Controls" to "HUNT Dimming".

Page #	Reference	Comment or correction
8-33	8.3.6	The Lighting Controls Council of the National Electrical Manufacturers Association and the Lighting Controls Association have each reviewed the Wisconsin Administration Building Study. Their comments follow: "The conclusions drawn from the Wisconsin Administration Building Study are invalid due to the use of unsound research techniques which departed from established norms of sample selection and methodology. 1. **Non Representative Sample.** This sample is not representative of the office occupant population. The study indicates that 20 of 21 people in the control group, which is comparable to the monitored group, "turned off lights manually 90 percent of the time." Therefore, it must be concluded that the sample consists of a special group of people who have been conditioned to turn off lights whenever they leave a room. All data obtained from this sampling are, therefore, invalid. 2. **Erroneous Methodology** The description of the method employed reveals an improper influencing of the test subjects by the field research staff. a. The occupants were informed that they were part of an experimental lighting project. They were even "given a short description of each of the control strategies." b. All 63 offices in the test were visited "at least once a week…between the hours of 6:00 a.m. and 4:00 p.m." Most offices were visited between 25 and 27 times." c. These two actions violate accepted research procedures because they draw special attention to the test and influence behavior. d. Given the intelligence and energy consciousness of the occupants, it is apparent that they were highly influenced just prior to and during the test to turn off lights in vacated offices."

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- California Energy Commission
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The principal authors of these Guidelines were James Benya of Benya Lighting Design, Lisa Heschong of Heschong Mahone Group, Terry McGowan of Lighting Ideas, Inc., Naomi Miller of Naomi Miller Lighting Design, and Francis Rubinstein of Rubylight. Barbara Erwine of Cascadia Conservation contributed extensive material on daylighting design. Nancy Clanton of Clanton & Associates, Mike Neils of M. Neils Engineering, Inc. and Douglas Mahone of Heschong Mahone Group contributed additional material.

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Existing and past members of the ALAC and its predecessor, the Advanced Lighting Professional Advisory Committee (ALPAC), have worked since the late 1980s to shape and mold the ***Advanced Lighting Guidelines*** through three editions. It is not possible to identify all the contributions, but a couple of individuals deserve special recognition. Norm Grimshaw of Advanced Transformer was the Chair for both the ALAC and the ALPAC and has worked tirelessly for more than 10 years to make sure that the ***Advanced Lighting Guidelines*** reflect the state-of-the-art in the lighting industry. Fred Berryman, former California Energy Commission staff, created the original ALPAC, arranged the initial funding, and provided clear vision for the first and second editions.

Finally, the 2001 Edition would not have been possible without the leadership and vision of Jim Benya, Lisa Heschong, Doug Mahone and Mazi Shirakh. Their efforts, from project conception through completion, helped identify funding resources, recruit authors, recruit ALAC members, and provided critical project leadership.

1. INTRODUCTION

1.1 About the Advanced Lighting Guidelines

The *Advanced Lighting Guidelines* were first developed in 1991 by the California Energy Commission to dispel myths about new and emerging advanced lighting technologies. The Guidelines were updated in 1993 by a partnership of the California Energy Commission (CEC), the Electric Power Research Institute (EPRI) and the U. S. Department of Energy (DOE). Previous editions have been used by designers, instructors and energy policy makers around the world and have been published in several different formats and media.

This document is the 2001 Edition of the *Advanced Lighting Guidelines*. It contains up-to-date information about the energy-effective lighting technologies covered in previous editions and extensive additional information. Material from the prior Guidelines has been updated and expanded, and obsolete material eliminated. Since 1993, some technologies, such as magnetic ballasts, have lost their position in the lighting market and their coverage has been eliminated from the Guidelines. Technologies such as T-5 lamps, which were just appearing on the scene in 1993, have begun to establish a foothold in the market and are treated in more depth in this latest edition.

The goal of the Guidelines update is to provide a comprehensive, living document that will remain useful to lighting decision makers and that will serve to encourage appropriate practice for lighting design in buildings.

The Guidelines are intended for use by architects, design-build contractors, lighting designers, electrical engineers, electrical designers, lighting educators, students, utility program managers, procurement officers, energy service project managers, government policy analysts, facilities managers, building owners, building financers, code enforcement officials and others who make decisions about lighting.

The New Buildings Institute is working to establish a system and secure funding to continuously update the *Advanced Lighting Guidelines* on a periodic basis. These updates will include expanding the number of applications in Section 5 as well as incorporating new technologies as they reach the marketplace. Additionally, future developments seek to increase and enhance the Guidelines' web-enabled functionality for the respective users described above. In essence, to create an online tool that remains live, up-to-date, and vital.

1.2 Inside the Advanced Lighting Guidelines

In addition to presenting information about state-of-the art lighting technology, the new *Advanced Lighting Guidelines* have been substantially reorganized. The 1993 guidelines were organized by technology, with separate guidelines for each of 12 types of technology (occupancy sensors, full-size fluorescent lamps, compact fluorescents, etc.). The new *Advanced Lighting Guidelines* are organized in seven broad chapters dealing with: Lighting and Human Performance, Lighting Impacts and Policies, Lighting Design Considerations, Applications, Light Sources and Ballast Systems, Luminaires and Light Distribution, and Lighting Controls. Discussions of daylighting design, rather than being sequestered in a separate chapter that might easily be overlooked, are now integrated throughout the *Advanced Lighting Guidelines* to help the designer better understand advanced approaches for integrating daylighting and electric lighting.

Below is an overview of each of the chapters in the *Advanced Lighting Guidelines*:

- Chapter 2, Lighting and Human Performance, provides an overview of the complex interrelationship of light and human vision, health and productivity. It's important that lighting professionals be aware of these issues and their relationship to the lighting design process, and that they be able to discuss these issues with clients and end users. The research and theories described in this chapter are important, sometimes controversial, and rapidly evolving. Lighting professionals are encouraged to keep abreast of new research published by the lighting industry, the scientific community, government agencies and others.
- Chapter 3, Lighting Impacts and Policies, is organized into three sections. Energy Impacts describes the impacts of lighting use on our electricity generation systems, on HVAC systems, and on peak electric loads. It also presents data on lighting energy use by building type, and as a percentage of whole building energy use. This information can help facility managers and others to understand where the greatest savings might be achieved with energy efficiency improvements.

  The Environmental Impacts section describes some of the impacts of energy use on the environment, discusses disposal issues related to lamps and lighting equipment, and provides an overview of concerns related to light trespass and light pollution.

  The Lighting Policies, Codes and Standards section provides an overview of energy policies, codes and standards related to lighting. U.S. national and state energy policies and codes are summarized, as are construction codes applicable to the lighting industry. This section is not intended to be an encyclopedic source of information about codes and policies; rather, it serves as a quick reference guide. Standards of design are also discussed, including a brief overview of the Illuminating Engineering Society of North America's (IESNA) recommendations and standards, and the lighting design criteria presented in IESNA's *Lighting Handbook, 9th Edition.*
- Chapter 4, Lighting Design Considerations, presents a series of advanced lighting design guidelines that address a range of lighting design criteria, from illumination levels based on light source spectrum to issues such as task and ambient lighting, daylighting integration, flicker, glare, modeling of faces and objects, and more. The strategies presented here are intended to enhance the IESNA design procedure, and to help lighting professionals achieve good quality lighting design that also gives energy efficiency and environmental impact a priority.

  This chapter also presents an overview of tools and computer programs to assist lighting designers, and presents economic analysis information to help designers, building owners and others evaluate the cost effectiveness of design options.

  Many of the lighting design strategies introduced in this chapter are illustrated in the models shown in chapter 5. In addition, the technologies and techniques are explored in greater detail in subsequent chapters that focus on Light Sources and Ballast Systems (chapter 6), Luminaires and Light Distribution (chapter 7), and Lighting Controls (chapter 8).
- Chapter 5, Applications, includes models demonstrating advanced lighting designs for eight applications: private offices, open offices, executive offices, grocery stores, big box retail stores, specialty retail stores, classrooms and gas stations. For most of these applications, more than one model has been developed to illustrate different advanced design approaches or different circumstances, such as lighting design for a space with daylighting compared to lighting for a space without daylighting. The light sources, ballasts, luminaires and control strategies shown in these models are described in more detail in later chapters.

- Chapter 6, Light Sources and Ballast Systems, discusses the technical and application aspects of advanced electric light sources, including tungsten-halogen and other high performance incandescent lamps; fluorescent lamps and their ballasts (including compact fluorescent lamps and electrodeless or induction lamps); high-intensity discharge lamps (including metal halide, high-pressure sodium and low-pressure sodium) and their ballasts; and light-emitting diodes. Technical aspects of using daylight as a light source are also discussed, including daylight availability and the spectral characteristics of daylight. This chapter complements the design guidelines presented in chapter 4 and the models shown in chapter 5 by providing details about the practical information necessary to analyze, specify, install and maintain light sources for optimum energy use and performance.
- Chapter 7, Luminaires and Light Distribution, provides practical information to help lighting designers select luminaires with the most appropriate light distribution and higher efficiencies. General luminaire selection criteria are presented, and daylight systems, including toplighting and sidelighting strategies, are discussed in detail. Information about specific types of advanced luminaires for interior and exterior applications is presented, including details about lamping and materials used, maintenance and operations issues, luminaire efficiency, and design and control considerations. As with chapter 6, this chapter is intended to build on the strategies presented in the Lighting Design Considerations and Applications chapters by providing more in-depth technical information about advanced luminaires and daylight systems.
- Chapter 8, Lighting Controls, describes advanced lighting controls that can be used to reduce lighting energy while enhancing lighting quality. The chapter presents an overview of user and energy savings issues related to controls, including a discussion of maintenance and commissioning issues. Devices and strategies for switching, dimming and occupancy sensing are discussed in detail, as are integrated daylighting controls, building-level controls systems, and other controls strategies. Many of the controls approaches presented here are illustrated in the models in chapter 5.
- Chapter 9, Appendix, contains a list of references cited in the *Advanced Lighting Guidelines* and a list of acronyms of organizations, government agencies and legislation referred to in the Guidelines.

2. LIGHTING AND HUMAN PERFORMANCE

Lighting enables humans to go about their lives, including work and play, as effectively as possible. It provides for our visual needs, and also safety and security. Lighting also has strong social and emotional significance. Figure 2-1 illustrates the wide range of issues and requirements addressed by lighting. Human needs are first and foremost. Since it's difficult to accomplish much when we can't see well, it's fairly obvious that lighting is crucial to human performance. This chapter addresses visibility, health, mood, and how lighting conditions might affect overall human performance. However, our ability to measure this impact is the subject of much discussion among lighting professionals.

The human eye is an enormously sensitive and adjustable organ, able to compensate for a vast range of conditions and able to function successfully under a wide range of visual environments. While visibility is generally well understood, many aspects of the eye-brain system remain to be fully explained. The challenge for lighting professionals is to understand under what circumstances certain visual conditions might be better than others, and to use that knowledge to design lighting systems that improve overall performance.

Lighting professionals must be aware of the relationships among lighting, productivity, human health, safety and security. They should be able to discuss these issues with clients and end users. Effectively addressing the concerns—both legitimate and unfounded—that people may express about lighting, is crucial to the lighting design process.

There are three general areas where light interacts with humans to affect their overall performance: visibility, mood and health. Each of these areas is being researched to better understand potential effects and mechanisms. Some research is highly structured and disciplined, while other research is more exploratory and intuitive. Ultimately, we will need a range of methodologies to fully understand the relationship of light to human performance, from artistic intuition to scientific research, from laboratory investigations to field experiments to large epidemiological studies. This field is exciting and rapidly evolving. This chapter reports on some of the current knowledge.

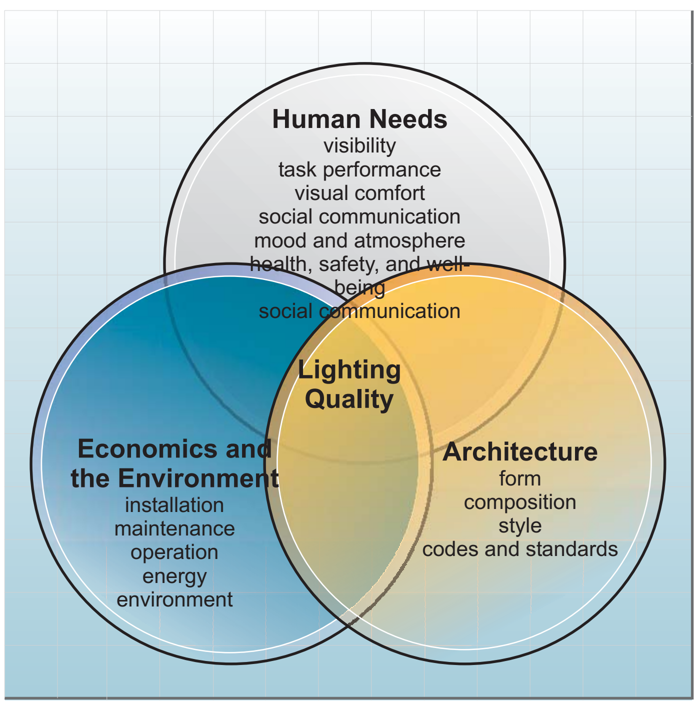

Figure 2-1 – Overlapping Lighting Issues
Source: IESNA Lighting Handbook, 9th Edition

2.1 Light and Vision

The key issue for any lighting installation is to help us see well. Efficient design strategies are primarily directed at achieving the highest level of visibility in a given situation with the minimum use of energy. To do this, we need to understand the determinants of visibility. Very often a task can be made more visible by modifying the task, rather than by adding additional illumination.

This section provides a brief overview of the mechanics of human vision. For a more thorough explanation, see the Illuminating Engineering Society of North America's (IESNA) *Lighting Handbook, 9th Edition*. The Handbook also discusses the determinants of visibility, and how these fit into appropriate lighting design. The new illumination selection procedure (chapter 10 of the Handbook) integrates a concern for lighting quality into the lighting procedure. Section 3.3.4 of the *Advanced Lighting Guidelines* addresses the new IESNA procedure in more detail.

Humans have an enormously rich and effective visual system. It has many capabilities, but also limits. It functions with a complex system of intricate muscles, lenses, photoreceptors, neural pathways and mental interpretation.

Many of the functions of our visual system are physical. First light passes through the transparent protective layer of the cornea. The iris, the muscular ring that determines our eye color, then contracts or expands to control the amount of light entering the eye. The light then passes through the lens, which changes shape via the working of the ciliary muscle to modify the eye's focal length, producing a sharp visual image on the back of the eyeball where the rods and cones create nerve impulses in response to the light’s stimulus. Vision problems due to imperfections in these physical processes can often be corrected with glasses, surgery, or simply more light to generate stronger nerve impulses from the retina. Figure 2-2 illustrates these basic structures of the eye.

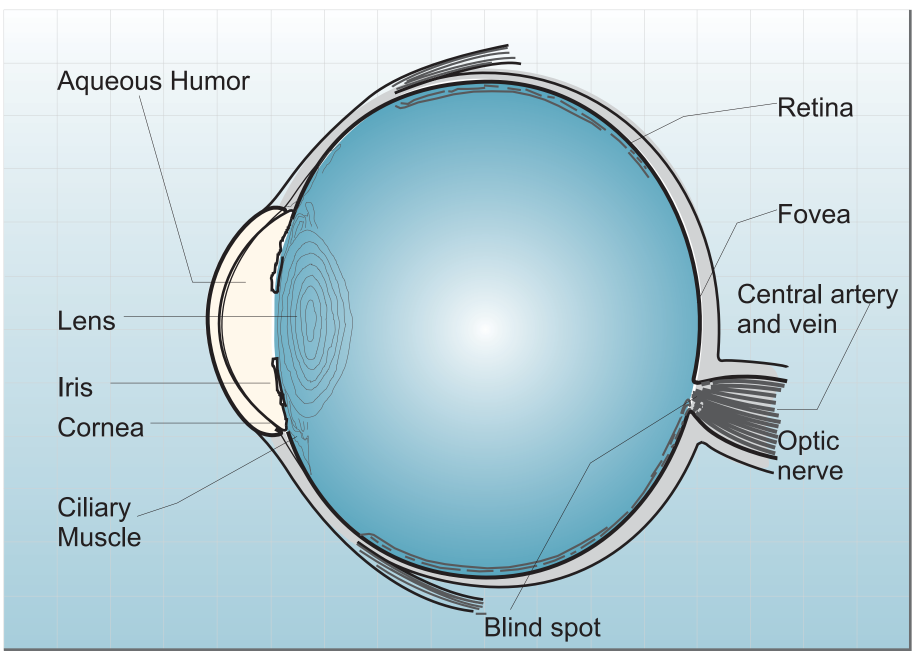

Figure 2-2 – The Human Eye
Adapted from IESNA Lighting Handbook, 9th Edition

Once light reaches the retina, the remainder of the visual process is biochemical and mental. These more subtle, and complex, processes are just as important to the functioning of our visual system as are the physical processes. A lighting designer needs to understand these in order to provide for good vision. They are the subject of much of the rest of this chapter on Lighting and Human Performance.

2.1.1 Illumination Range

The visual system perceives the luminance of an object, or the amount of light emitted or reflected off of a surface, measured in candelas per meter squared. However, we most commonly speak of lighting levels in terms of illuminance, or the amount of light incident upon the object, measured in footcandles or lux. For a given reflectance of a surface, we can see things over an enormous range of illumination conditions, from about 1 lux to over 100,000 lux. Illumination levels on a moonlit night may vary from 1 to 10 lux (roughly 0.1 to 1 footcandle); bright sunlight from 50,000 to 100,000 lux (roughly 5,000 to 10,000 footcandles). But at any given time, our eye can only process information from a limited range of about three orders of magnitude (see Figure 2-3). For example, the eye can successfully see from about 1 lux to 1000 lux, or 100 lux to 100,000 lux. Typical office environments may range one order of magnitude, such as from 100 lux to 1,000 lux (10 to 100 footcandles).

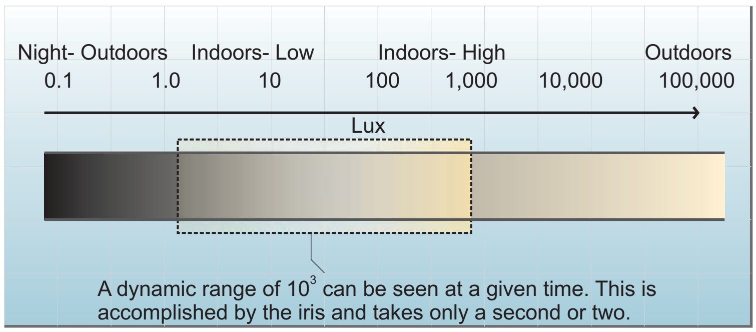

Figure 2-3 – Illuminance Range of the Eye

Adaptation to different illumination levels involves three processes. First the pupil size changes. The pupil can constrict in response an increase in light levels about five times faster than it can dilate in response to a drop in light levels. Both processes typically occur within a fraction of a second. The second process is neural adaptation, that is, a change in neural sensitivity. This process is extremely fast (on the order of milliseconds) and can accommodate up to three orders of magnitude of illumination levels. This allows us to instantly adapt to a range of illumination levels typical of most interior spaces. The third process is photochemical adaptation, involving the bleaching and regeneration of the pigments in the rods and cones under more extreme ranges of illumination. The cone system can regenerate within 10 to 12 minutes, while the rod system may require up to 60 minutes for full regeneration. Thus, adapting to darker environments takes considerably longer than adapting to bright environments, and adapting to very low levels of light (where only the rods are active) can take quite a while. This is commonly experienced by people who enter a movie theater on a bright sunny day.

Because the eye so readily adapts to different light levels, it generally is not a good judge of absolute illumination levels, as would be measured by a light meter. Rather, we tend to compare relative brightness between the darkest and brightest areas within our field of view. Thus, to a dark-adapted person a dimly lit surface may appear very bright, while just moments later, if that person becomes bright-light adapted, the same illuminated surface may appear dark.

Adaptation is especially important when moving from indoors to outdoors. During the day, interior light levels may seem very dark to people who have adapted to daylight. Similarly, at night, people adapted to bright interior light levels may be rendered temporarily "night blind" when they step outside. The eyes of older people are slower to adapt and thus even more sensitive to changes in light levels. Good lighting design takes the adaptation level of the viewer into account and may provide a transition area to provide time for the viewer to adjust to new light levels. For further discussion of adaptation, see the sections on Aging (2.1.6), Light Trespass (3.2.4) and Glare (4.3.2). Also, many of the applications in chapter 5 address adaptive compensation strategies, and chapter 8 provides information about controls strategies for adaptive compensation (8.6.1).

2.1.2 Color

Color vision is one of the great joys of being human. Most of us can distinguish an enormous range of subtle colors, and find pleasure in doing so. Colors add meaning to our environment (see Figure 2-4), and color discrimination is an important function of many visual tasks, especially those involving any natural materials. Being able to see accurate colors is especially important in certain settings, such as health care facilities, where it's important to be able to observe subtle changes in skin tones, or retail, industrial or scientific environments where color matching is an essential function.

Figure 2-4 – The Added Dimension of Color
Color adds a considerable amount of information to our view of the world. Photos courtesy Lisa Heschong.

Our eyes can interpret colors across most of the visible spectrum. However, we are most sensitive to light in the green-yellow (550 nanometers) portion of the spectrum. Daylight and sunlight provide illumination across the entire color spectrum, but change in content over the course of the day. Electric light sources vary widely in their spectral content, and should be carefully selected for their color characteristics. See sections on chromaticity and color rendering (6.2.4), and spectral characteristics of daylight (6.3.4) for further information.

Being able to see color is a function not only of the eye's sensitivity, and the intrinsic color of objects, but also of the brain's adaptation and the spectral content of the light. The mental interpretation of colors is not a constant function, but relative. The brain compares one color to another, and looks for the "bluer" or "greener" of the two. It tries to use the whitest object in sight as a reference point; thus, subtlety changing a color of white from bluish-white to pinkish-white may influence the interpretation of other colors.

The spectral content of light in a space is a function not only of the light source, but also all the other colors nearby that may be reflecting the light. Red-colored surfaces, for example, reflect red light and absorb other colors. Thus, a large area of red in a room will actually make the light in the room have more red content and make other surfaces appear redder also. This is why paint colors intensify as more surface area is painted.

The lighting designer should be aware of all the influences on color appearance within a space, including sources of daylight, color tints of window glass, spectral content of electric light sources, reflective surfaces, and the color of specific tasks. The spectral content of light sources, including daylight, and their apparent correlated color temperatures, or the "whiteness" of the light source, are discussed further in sections 6.2 and 6.3. Choices of lamp types for different applications are discussed in sections 6.4 through 6.8.

2.1.3 Visual Size

The visual size of an object is one of the most important determinants of how easy it is to perceive that object. The larger an object is relative to our visual field, the easier it is to see. Thus, as things come closer to our eye, they appear larger, and we are able to discern ever-smaller details.

One of the limits on the level of detail that we can make out is the focal precision of our eyes. At higher light levels, we can see smaller details more precisely. The closer an object is, the larger it appears in the visual field, and so the more detail we can see (as long as we can focus that closely).

Visual acuity is defined by degrees of arc, or the diameter of the visual cone that is intercepted. People can typically perceive details on the order of minutes of one degree of arc (1/60 of 1 degree). Thus, humans can perceive very small objects indeed, especially if the objects stand out against a contrasting background, such as a star against a black sky, or a speck of dirt against clean white enamel paint.

The greater visual challenge is distinguishing shape, which is critical in tasks such as reading letters of the alphabet. Indeed, reading is one of our more challenging visual tasks, especially since we try to do it so quickly. Just a few occasional errors in discriminating between letters can be disastrous for some office tasks, such as analyzing numbers or reading medical files. Small font size requires higher illumination in order to discriminate between the fine details of the letters.

Thus, increasing the size of the visual task, such as increasing the standard font size of printed material, can reduce the need for higher illumination. Providing larger printed letters or magnification for those people who require them may be an excellent way to meet the critical seeing needs of people with suboptimal vision (which generally includes everyone over the age of 45) without adding more lighting everywhere in a facility.

2.1.4 Contrast

Contrast is one of the most fundamental elements of vision; lack of contrast can reduce visibility to nil. There are three kinds of contrast that our visual system processes: brightness contrast, pattern contrast and color contrast. Cheetahs and zebras and chameleons have all taken advantage of this by developing visual camouflages that hide predator from prey, and prey from predator. Brightness contrast results from variations in the amount of light reflected or emitted from a surface, such as due to shadow patterns, changes in dark against light colors (see Figure 2-5), or surface shape and texture. Pattern contrast is the perception of changes in a regular pattern, as when the pattern of stars and stripes on a flag changes perspective as the flag waves. Color contrast is based on the juxtaposition of different colors next to each other. Complimentary color pairs, such as red-green or blue-yellow, are likely to result in the greatest visual contrast.

Figure 2-5 – Visual Contrast
Lack of contrast can reduce visibility.

Increasing the contrast between an object and its surrounds increases the visibility of the object, and reduces the need for additional illumination. For example, the old office before computers included many tasks with low contrast, such as fuzzy carbon copies and handwriting in pencil. With the advent of laser printers and copy machines, most paper-based office tasks now have much higher contrast, and therefore can be adequately performed at lower illumination levels.

Increasing the level of contrast can be especially useful in signage and retail design, where it can increase visibility while lowering illumination requirements. Using white lettering on dark backgrounds has reduced the illumination needs for roadway signs. Similarly, color contrast can often be used to distinguish products or labels more successfully than increased illumination.

2.1.5 Motion

Typically, our eye is in constant motion, rapidly scanning the scene of interest with our central vision. The brain then constantly fills in the picture from previous information received moments earlier. Focusing on a moving object requires concentration on just that object, and interferes with the general scanning process. The more predictable the motion, and the slower the motion, the easier it is to maintain focus on the object. Thus, we are likely to have less precise vision of a moving object than a stationary one. Likewise, when fixating on moving objects, our peripheral vision becomes blurred. Ball players are trained to keep their “eye on the ball,” fixing their focus and attention on a moving object. In general, the faster something is moving the less detail can be distinguished. However, increasing size and contrast will increase visibility. For example, using an orange tennis ball makes it easier to see against green vegetation or a blue sky.

Motion in our field of view naturally attracts our visual attention, and our central vision is redirected to investigate. This is important in certain tasks, such as driving at night, because an object detected in the periphery of vision often causes the driver’s visual attention to be momentarily diverted from road to object. In addition to actual motion, changes in the illumination of stationary objects, such as flashes or flicker, also draw our attention. While flashing does not increase visibility per se, we are more likely to notice and remember an object illuminated with flashing light. The flashing lights on emergency vehicles take advantage of this phenomenon, as do marketers who grab our attention with flashing neon lights or quickly changing TV commercials.

2.1.6 The Aging Eye

As the eye ages, it becomes less responsive. The scanning function moves a little more slowly, and adjustments to different light levels occur more slowly. The lens becomes increasingly rigid and loses some ability to adjust focus, especially in the near field. The lens typically becomes more yellowed and more light is scattered within the eye, also causing a loss in visual acuity and contrast sensitivity. Thus, beyond the age of 40 people typically start needing more light to see small details, and often need glasses to help them focus in the near field. Because of the increased scattering of light in the eyeball, glare sources also cause a greater loss in visual function in older people.

In addition to normal aging, older people are subject to many diseases of the eye. Macular degeneration has become increasingly common in recent decades. It involves a loss of function of the external area and greater reliance on peripheral vision for both navigation and reading.

The loss of visual function for the older population is an important issue as our general population ages, and as businesses work to comply with the federal government’s Americans with Disabilities Act (ADA) requirements. Accommodating the aging eye is especially critical in health care facilities, senior care homes and outdoor lighting in public spaces. For more information, refer to the recently updated IESNA Recommended Practice publication, "Lighting and the Visual Environment for Senior Living."

2.1.7 Photopic and Scotopic Vision

Humans actually have two distinct visual systems—rods and cones—that function quite differently, but work in concert to provide our vision.

The rods, which are relatively uniformly distributed across the retina, contribute to our peripheral vision and are particularly effective at modest and low light levels. The rods, most sensitive to shades of gray and motion, seem to be a very old visual system in evolutionary terms, as we share it with most other animals. The second visual system consists of the cones, which allow us to see color. They are strongly concentrated in the small central area of the retina called the fovea. This system is shared with only a few other animals, such as our close relatives, chimpanzees.

Figure 2-6 shows the relative distribution of rods and cones across a section of the eye. The blind spot occurs where the optic nerve is attached to the eye. The zero-degree point represents the fovea, or focal center of the eye. The rods are absent in the fovea, and increase quickly in number up to about 20 degrees from the fovea, then gradually decline toward the outer edges of the retina. Cones are most highly concentrated in the fovea, but are represented at a lower concentration throughout the retina.

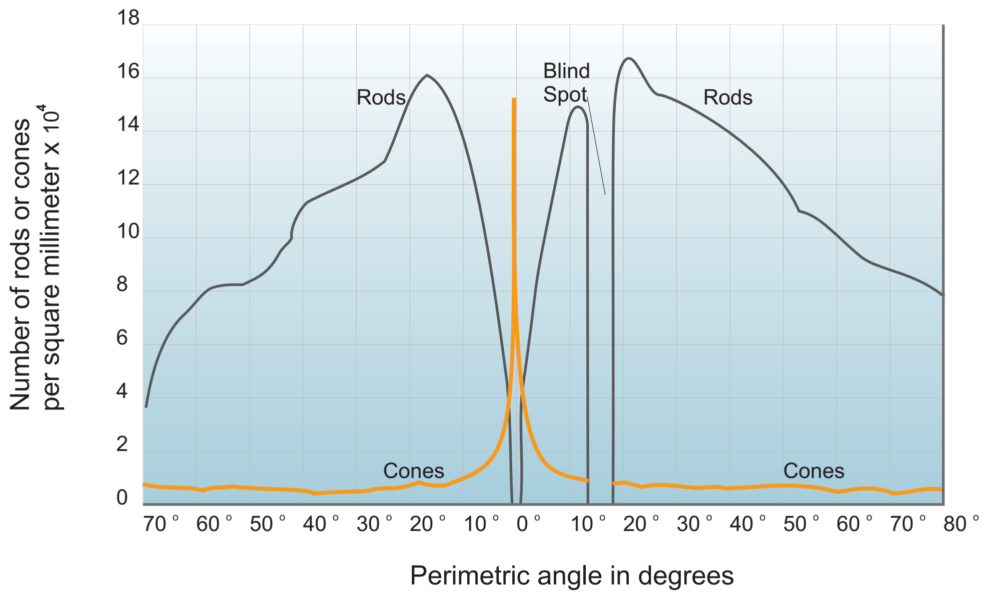

Figure 2-6 – Distribution of Rods and Cones in the Retina
Source: IESNA Lighting Handbook, 9th Edition

Peripheral Vision

Our peripheral vision is based on information from the numerous rod photoreceptors, distributed around the periphery of the retina, along with a much smaller number of cones that provide color vision at normal light levels. It allows us to see in about a 70° conic field of view. The rods are much more sensitive to low illumination levels and are most sensitive to blue-green light. Research suggests that rods influence pupil size, and thus are very important to our light adaptation level. Peripheral vision is also very important in detecting motion and helping us judge our own movement.

Foveal Vision

A small area of the central retina, called the fovea, provides detailed, color vision in about a two-degree cone of the visual field. (Two degrees is about two thumb widths at arm's length.) The fovea contains a very high concentration of cones at the center of the retina. Three different spectral sensitivities enable the cones to provide us with continuous color discrimination. A highly evolved stimulus system directs the movement of the eye to maintain focus on objects of interest throughout the visual field. The numerous small muscles of the eye are continuously moving and adjusting the eye to maintain this focus, which can be only partially voluntarily controlled.

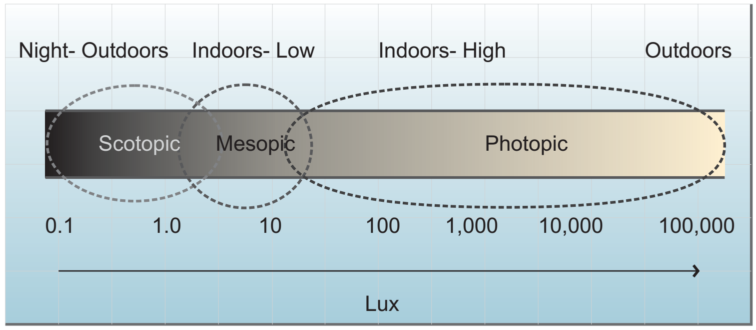

Figure 2-7 – Scotopic, Mesopic and Photopic Ranges

These visual systems normally function seamlessly together, with the focal system directing the center of our attention and the peripheral system filling in the visual context. However, when illumination levels become too low for the cones, the rods in the peripheral system start to take over. Together, our visual systems function in three modes: photopic, mesopic and scotopic.

- *Photopic vision* is defined as vision at relatively high light levels where the cones are fully activated. It occurs at illumination levels above 3 footcandles. This is commonly called "day vision." Almost all research on visual acuity and visual preferences has occurred in the illumination ranges from 50 to 200 footcandles, to represent indoor work environments. Illumination meters are typically adjusted to the ranges of sensitivity of the eye in this range.
- *Scotopic vision* occurs at illumination levels under which the cones cease to function, at substantially less than 1 footcandle, such as those illuminances experienced on a starlit night. It is commonly called "night vision." With scotopic vision, there is no perception of color, and central, or foveal, vision is impaired.
- *Mesopic vision* occurs in the state between the photopic and scotopic extremes. In this state both rods and cones are active. It is typically experienced at dusk and under a bright moonlit sky, and includes almost all outdoor lighting conditions. As illumination levels decline, focal vision decreases and color perception also declines. Similarly, there is a shift in spectral sensitivity from the yellow-green peak of the cones to the blue-green wavelength peak of the rods.

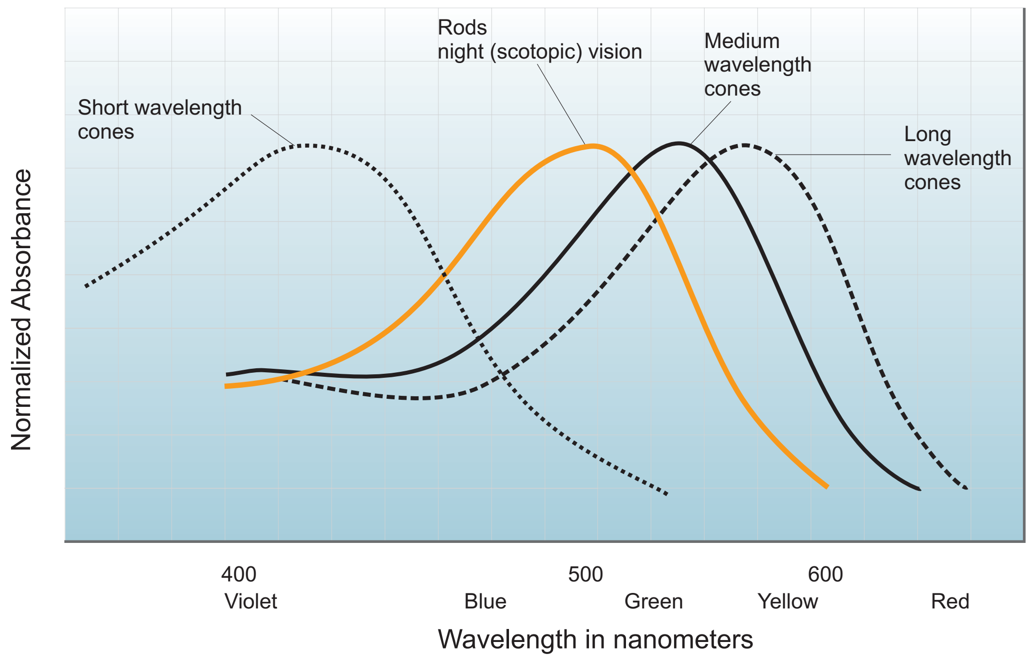

Figure 2-8 – Spectral Sensitivity of Rods and Cones
Source: Bowmaker and Dartnall 1980

It's clear that the eye has different visual responses to the light spectrum at different illumination levels (see Figure 2-8). This has two implications for lighting design. The first relates to visual performance under low light conditions at night, and the second relates to visual performance under typical office illumination levels.

- *Night Conditions.* Some research suggests that this difference in visual response has implications for the specification of outdoor lighting systems at night (under 0.5 footcandles, or 5 lux). If peripheral vision, contrast detection, and sensitivity to motion are key concerns for outdoor night lighting, as they might be for security lighting or roadway vision, then using blue-rich lighting to preferentially stimulate the rods may be important. This work suggests that metal halide lamps would be a better choice for peripheral detection under street and roadway lighting than high-pressure sodium lamps because of the increased light output in the blue range of the spectrum in metal halide lamps (Rea 1999). It is important to note that—other than color detection—central or foveal visual acuity does not differ significantly under metal halide or high-pressure sodium sources at equal illumination levels. (Outdoor luminaires are discussed in section 7.6.)
- *Office Illumination Conditions.* Another set of researchers is concerned with the impact of the spectrum of light on vision at workspace illumination levels. The pupil size is primarily determined by the stimulation of the rods outside of foveal vision. Because the rods are more sensitive to bluer light than the cones, for the same level of illumination, the pupil is smaller for ambient light sources that are richer in the blue spectrum. Research indicates that under blue-rich ambient light, smaller pupils tend to increase the observer's depth of field and visual acuity compared to blue-deficient ambient light. Because of this interaction with pupil size, light sources with more blue (also referred to as "scotopically enhanced"), such as daylight or high correlated color temperature fluorescent sources (4000–6500°K) seem to appear brighter to observers. This work suggests that for the same level of illumination, observers will see things more acutely under ambient light sources that are richer in blue light.[1]

[1] See Navvab 2000 for a discussion of the differential impact of spectral content on focal versus peripheral vision.

Both design responses are controversial and lead to conclusions that might affect lighting practice in far-reaching ways, beyond just the immediate concern for spectral sensitivity and visual acuity. For example, the use of metal halide lamps for outdoor lighting has been found disruptive to some animal behaviors and astronomical observations. In office and workplace lighting many people consider high color temperature lamps to be harsh and unattractive. Lighting designers should be aware of the issues and discussions about these theories and carefully weigh conflicting criteria.

2.1.8 Vision and the Brain

The eye is a dynamic system that is constantly adjusting to its environment. The pupil opens or closes to let in more or less ambient light. The lens adjusts to focus on objects near or far. But there are even more subtle changes going on. The chemistry of the rods and cones inside the eye also adjusts to light conditions, as does the sensitivity of the nervous system that carries messages to the brain.

However, vision is determined not just by the physical process within the eye, but also by how our brain interprets those messages. It is possible to have a functioning eye and still not be able to “see” because the brain cannot make sense of the input from the eye. The processing inside of the brain helps determine what we expect to see and how we interpret it. It turns out that the process of vision is a two-way street. Human beings can “visualize” a scene by simply imagining it. Neurologists hypothesize that this visualization capability is derived from the intensive feedback that the brain provides to the eye as the brain interprets visual signals.

The visual cortex is one of the largest and most complex portions of our brains. Human brains are dominated by their visual capabilities, in contrast to other animals that have more brain power devoted to other sensory inputs. Humans can process an astonishing amount of visual information, and indeed seem hungry to do so. Variety and interest in the visual field are an important source of mental stimulation. Variety and interest may be an important aspect of eye health (discussed in section 2.1.9), and may also be an important attribute of good lighting design's contribution to improved productivity (discussed in section 2.3).

Visual cues are also extremely important to the formation of memory. Most people are “visual learners” who remember things best that they have seen. A rich visual environment helps set the context for these memories and may actually improve memory retention. Memories are usually attached to information about time and place, both of which can be informed by the quality of light, especially daylight, which varies by time and place.

To be useful to us, light must be given meaning; it is the brain that makes sense of the light stimulus processed through the eye. Light stimulus that can be recognized in meaningful patterns is accepted as information. Light stimulus that does not form a meaningful pattern becomes “visual noise,” ignored by the conscious mind, and potentially interfering with the processing of useful information. A challenge for lighting designers is to try to use light as a way to add order and information to our environment. Meaningful illumination of architectural elements does this, helping to define a place and inform our wayfinding through that space. Similarly, illumination by daylight within a space, especially daylight associated with views, can provide a huge amount of information about time and place. Chaotic or random lighting patterns, on the other hand, can increase our stress levels and sense of disorientation. This may be purposely used in certain settings, such as entertainment environments, but is not usually a sign of effective lighting.

2.1.9 Computer Use and Vision

The introduction of the personal computer into the workplace radically transformed workers’ visual needs. Today, there is increased awareness about the visual and health needs of workers who use computers.

Optometrists are coming to believe that people who use computers extensively should follow special procedures to ensure eye health. Regular eye examinations and the wearing of proper glasses or contact lenses are extremely important. Many people wear reading glasses adjusted to book distance, but not to the distance of computer monitors. No lighting or computer screen improvement can eliminate this focal distance problem.

Physicians have also seen many cases of eyestrain, headaches, neck strain and eye dryness that seem to be related to computer use. In addition to recommending ergonomic, glare-free workstations, they typically recommend that a worker have access to a long-distance view, 20 ft or more away from his or her workstation, that allows for a change of eye focus to relax the eye. They recommend that workers look away from the computer every five minutes or so to change focus and relax their eyes.

Another fairly common symptom associated with computer use is eye dryness, most likely due to lack of blinking. Again, changing focus away from the computer encourages a faster rate of blinking and better eye health. Thus, providing areas of visual attraction outside of workstations, such as views of windows, interior plants or artwork, would seem the best solution to promote eye health for the predominantly computer-based worker.

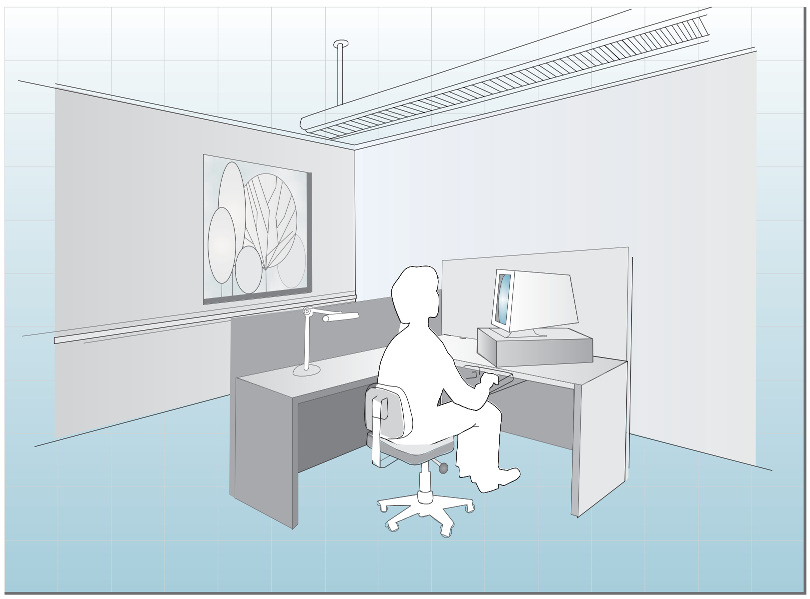

Figure 2-9 – Computer Worker with Far-field View

For design strategies to avoid veiling reflections in computer screens, see the discussion of reflective glare in section 4.3.2

2.2 Light and Health

Light is a “biologically active element” and profoundly affects human life and health. Photobiology is the study of this relationship, which is discussed in this section.

The timing and spectrum of light are known to affect plant growth. Nursery growers commonly use the timing of dark and light in their greenhouses to control the bloom of flowering plants. Having enough poinsettias for the winter holidays and roses for Valentine's Day is largely a matter of simulating the proper seasons in the greenhouses. Similarly, poultry ranchers use dark and light patterns to control the growth and sexual maturation of chickens and turkeys, so that there are plenty of eggs for Easter and turkey for Thanksgiving when consumers want them. This effect of light exposure and day length on animal growth, activity and sexual maturity has probably been the most extensively researched and understood in poultry ranching (IESNA 2000, 5-23).

Within the last decade there has been an expanding research effort to understand the biological effects of light on humans. This is being simultaneously pursued at the biochemical, cellular, organism and epidemiological levels, and includes research into circadian rhythms, hormone regulation, immunological response, psychological response, and human growth and development. Our luminous environment can no longer be considered merely a visual issue. The light we are exposed to both during the day and night interacts with some of the more fundamental biological processes of our body. Some of the recent research advances are discussed below.

2.2.1 Melanin, Vitamin D and Medical Uses of Light

It is well accepted that human exposure to light, especially exposure of the skin to the ultraviolet (UV) wavelengths in daylight, contributes to the manufacture of melanin in the skin, resulting in a “tan” for light-skinned people. Skin exposure to light also results in increased manufacture of vitamin D, and the resulting absorption of calcium. Rickets and osteoporosis are two diseases for which exposure to a modest amount of sunlight is preventative. Light is used for the clinical treatment of infant jaundice, where exposure to certain wavelengths, especially in the blue range of the spectrum, reduces the incidence of jaundice in very young infants.

Over the past several years, there has been an explosion of information regarding the immunological effects of ultraviolet radiation and visible light on the immune system. Photoimmunology is the discipline that investigates these issues. Simultaneously, the medical profession is learning to use light exposure (some visible light, but mostly UV-A) in combination with specific drugs to induce cell death in some types of cancer tumors (for more information about the effects of ultraviolet exposure, see section 2.2.7). It has also been realized that certain drugs and nutrients can alter the sensitivity of individuals to sunlight or certain spectra, and consequently alter their risk factors for some diseases or photosensitivity disorders. While much of this research involves exceptional levels of exposure, it is likely to unlock clues about the molecular basis of these cellular photo responses, and will help to identify the specific spectrum, intensities and timing that are involved. These exciting developments in medical research may eventually spill over to inform our understanding of more everyday levels of exposure to light, both daylight and electric.[1]

2.2.2 Circadian Rhythms, SAD and Jet Lag

Light is one of the external cues that biological systems use to set their internal clocks. Exactly how this process works, at what biological levels, and which biochemical pathways are involved is just beginning to be understood.

One of the first advances in understanding the relationship between light and human circadian rhythms came with the successful treatment of seasonal affective disorder, or SAD. Some people, who become depressed as the length of day shortens with the onset of winter, may be treated with exposure to bright light in the morning. Bright light before 10 AM, from either daylight or an electrical source, helps reset their biological clocks. There is a north-south pattern of SAD in the United States, with far more people reporting SAD symptom at the highest latitudes (greater than 30%) than the southern end of the country (less than 5%). Fluorescent light, because of its high efficiency and low level of heat output, became the preferred source for SAD treatment.

With the documented success in treating SAD, other applications of bright light are being studied to reset circadian rhythms, such as for people experiencing jet lag or night shift workers.[2] Bright lights suppress the production of melatonin, a hormone secreted primarily in the brain at night. By resetting the melatonin cycle, the circadian rhythm can presumably be reset. Thus, experienced travelers have learned that stepping outside into the daylight first thing in the morning can help reset their biological clock to the new time zone.

Darkness at night is just as significant as morning light. At night, the presence of melatonin affects sleep cycles and the production of a host of other hormones, notably estrogen. During the day, when melatonin levels drop, the levels of other hormones and neurotransmitters, such as serotonin, are seen to rise. Recent research suggests that nocturnal exposure to light may be the dominant

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[1] See http://www.pol-us.net and http://www2.kumc.edu/instruction/dpc/develop/index.htm for resources on photobiological research.

[2] The National Center for Biological Timings, which coordinates many of the studies of light and its relationship to the human biological function, is housed at the University of Virginia, http://cbt4pc.bio.virginia.edu.

regulator of circadian rhythms. Exposure to light at night, even of short duration or at low levels, may shift or interfere with the cycle of melatonin production. Current research is trying to determine how sensitive these biochemical mechanisms are to the quantity of light, the timing and duration of that exposure, and if the effects are spectrum specific (Raloff 1998a).

Circadian rhythms seem to follow a sinusoidal pattern, and external influences on the process can have different effects at different times of the day. For example, exposure to bright light during the early night delays the clock's phase, whereas in the late night the clock's phase is advanced (Ding et al. 1998).

Some researchers are concerned that exposure to light at night might prove to be an endocrine disrupter with the potential to increase cancer risk. The "melatonin hypothesis" holds that long-term environmental perturbations in natural rhythms of melatonin secretion—by exposure to electromagnetic fields or to light at night—might increase cancer risk, especially in the sexual organs, by increasing estrogen exposure (IESNA 2000, 5-11). Researchers at the National Institute of Environmental Health Sciences (Baldwin and Barrett 1998) explain: "The reduction of melatonin at night may alter the production of other hormones, may suppress the immune system's ability to recognize and respond to newly emerging cancers, and appears to spur the growth of at least some tumor tissues."

For many years it was assumed that the eye was the only biological system that received light, and that all responses to light must therefore be mediated by the optic nerve. However recent research has essentially shown that the physiology of the circadian photoreceptors is different from that of visual photoreceptors. A recent study published in *Nature* found that even individual animal cells isolated in culture maintain a circadian rhythm, and are directly entrained by light.[1] Other researchers have identified at least two genes, which seem to exist in all mammalian cells, that maintain a clock-like cycle of protein fabrication and re-absorption that is just slightly longer than 24 hours (Young 2000). Thus, it is conceivable that light has a much broader effect on our bodies than just through the visual pathways.

Much remains to be understood about how light interacts with the biological mechanisms of human circadian rhythms. In the decade to come we should be gaining more insight into the impact of illumination levels at different times of the day or phases of the cycle, the effects of specific wavelengths, and significance of the duration of exposure. This information is likely to contribute to a greater appreciation for diurnal variation in our luminous environment, and influence the discussion of such issues as the lighting of institutional environments, the use of daylighting strategies, nighttime adaptation, light pollution and light trespass.

2.2.3 Eye Development

There has been a medical controversy over whether exposure to light can affect early infant eye development. Earlier studies have found that the eyes of young animals, chicks and monkeys grew abnormally when deprived of periods of darkness (Stone 1997; Wallman 1993; Raviola and Wiesel 1985). Attempts to find similar effects in humans have been inconclusive. Some researchers suspect that exposure to bright light in nurseries might predispose premature infants to blindness or poor sight. In one recent experiment, the use of protective goggles failed to show any change in the incidence of blindness in premature infants (Phelps et al. 1997).

Other studies have looked at whether exposure to light at nighttime predisposes young children to develop myopia, or elongated eyeballs that result in nearsightedness. One study found a strong correlation between night lights in nurseries for children one to two years old and later myopia (Quinn et al. 1999). But follow-up studies by other researchers did not confirm these findings, and instead found a tendency of myopic parents to have myopic children, and also to use night lighting for their children (Zadnik, Gwiazda et al. 2000). Anthropological studies have found more myopia among children of industrialized peoples than they found among similar ethnic groups living in more less

[1] Zebrafish cells grown in culture are shown to be directly light responsive (Whitmore, Foulkes and Sasone-Corsi 2000).

developed conditions. Increased exposure to electric light is one possible cause, but far from proven. It is hoped that future research will clarify the relationship of the use of electric light to eye development in young children.

2.2.4 Full-spectrum Light

Daylight provides a complete spectrum of light. The visible portion is white light, consisting of all of the colors of the rainbow. Daylight also includes radiation that we cannot see—infrared light (radiant heat) and ultraviolet (UV).

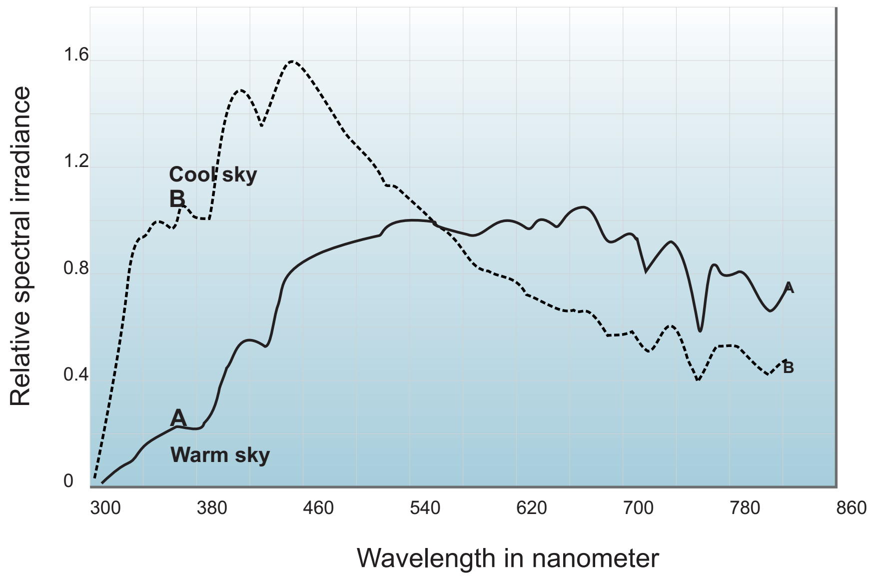

Figure 2-10 – The Various Spectra of Daylight
Adapted from Relative Spectral Irradiance Distribution of the Standard Phases of Daylight by Peter Boyce

Electric sources of light have very different patterns of spectral composition than daylight. Indeed, these spectral patterns are so unique that one can easily identify a lamp by a graph of its spectral power distribution. Chapter 6 discusses the spectral content of different light sources.

To faithfully reproduce all possible colors, the light source must contain all the colors of the rainbow in roughly equal proportions. Sources that produce all colors are referred to as “full spectrum." Daylight, by its nature, is “full spectrum.”

Some lamp manufacturers make fluorescent lamps that attempt to simulate the daylight distribution as best as technology allows. These lamps are sometimes advertised as providing "natural" or "healthy" light. They use the older, less efficient phosphors (halophosphors) to produce a wide range of the light spectrum. However, there is no official definition of full-spectrum lighting; the definition varies from manufacturer to manufacturer. These lamps are distinguished by having a higher proportion of their light at the blue end of the spectrum, along with more ultraviolet (UV-A) output and substantially lower overall efficiencies than standard fluorescent lamps.

Most modern, efficient fluorescent lamps (such as T-8 lamps) use a blend of rare-earth phosphors that produce light only in certain key regions of the visual spectrum that combine to produce white light. These lamps, while they do not produce all wavelengths, can have very high color rendition abilities.

There have been many claims made about the positive effects of “full-spectrum” lamps on people.[1] There has also been a considerable amount of research attempting to substantiate these claims.

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[1] In 1985 the U.S. federal government issued an injunction against one manufacturer of full-spectrum fluorescent lamps to prohibit them from making unsubstantiated health claims.

Unfortunately, much of this research has been seriously flawed by researcher prejudice or poor methodologies (Gifford 1993).[1] While any benefits of full-spectrum light have not been proven, neither have they been disproved. What is needed are carefully constructed research efforts that can pass scientific scrutiny.

2.2.5 Light and Mood

People intuitively know that light affects their mood. The lover sets a romantic mood with a candlelit dinner, and the stage designer chooses a glaring, high-contrast spotlight to set a menacing mood for a dramatic play. The ethereal light of a cathedral sets a contemplative mood, while the flashing neon of downtown excites.

The artistic tool kit of the lighting designer for theater, movies and other entertainment venues such as casinos and nightclubs is based on an understanding of the emotional effects of lighting. The palette of the lighting designer includes such lighting attributes as color, intensity, sparkle, reflectance, glow and the contrast of shadows and highlights. All of these attributes can be controlled to create a mood and make a setting memorable, much the way a musical composer selects tone, rhythm, tempo, harmony and pitch to create a distinctive song. Engaging lighting design can make a place or experience truly unforgettable. The edgy lighting of an Alfred Hitchcock movie is as memorable as the gentle dawn light in Yosemite captured in an Ansel Adams photograph.

While good lighting designers may intuitively understand the emotional effects of lighting, there has been little scientific research to substantiate or quantify these effects. Some people believe that the color of rooms, or the spectrum of light sources within the room, may affect mood, arousal or alertness. Perhaps the greatest difficulty here is precisely defining differences in mood on a useful and standardized scale. As we understand more about the interactions of light and health, we may also be able to identify other links to mood and emotional effects.[2]

There does seem to be some cultural consensus that certain lighting styles result in certain moods: such as believing that small pools of incandescent light create a home-like atmosphere and therefore are mentally relaxing, or that cooler color temperature fluorescent lamps (4000–6500°K) provide a more stimulating work environment. However, researchers at Natural Resources Canada (Veitch and Newsham 1996) found that lighting preferences actually vary by country and continent, and thus may be influenced by cultural and/or climatic associations.

2.2.6 Flickering Light

Flickering light can cause physiological problems, as any person who has experienced a strobe light-induced headache can attest. Indeed, extreme cases of nausea and even epileptic-like seizures have been observed in Japanese children watching cartoons with strong stroboscopic effects. While it is understood that flickering light can produce biological impacts outside of visual awareness, the exact mechanisms and the types of non-visual flicker that might have negative effects are not well understood.

There are subgroups of the general population that are more sensitive to flicker effects than others and some research has focused on these self-declared sensitive people. Although the sensitive subjects could not correctly distinguish if a hidden light source had a low or high rate of flicker, they were very likely to report more negative effects for sources with low flicker rates.

Solutions to flicker problems are discussed in sections 4.3.2 and 6.5.4.and include: using electronic ballasts for fluorescent lamps; adding phosphors; changing the phase of some of the light sources, especially for HID lamps; and adding daylight into the space.

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[1] See discussion posted at Web site: http://www.cisti.nrc.ca/irc/fulltext/ir659/contents.html for pros and cons of research on full-spectrum lighting.

[2] For a more detailed discussion of the status of current research on lighting and mood, refer to the *IESNA Lighting Handbook, 9th Edition* discussion on "Perception of Lighting" in Chapter 3, Vision and Perception.

2.2.7 Ultraviolet Light

Daylight, and some electric sources, also includes ultraviolet (UV) radiation. Ultraviolet levels from daylight are increasing across the globe due to ozone depletion, and are a concern for public health. All UV radiation should be considered potentially biologically harmful in extended doses. It ages both the skin and the sensitive tissues of the eye, and is strongly associated with increased risk of skin cancers.

UV radiation is split into three categories according to wavelength. The shorter the wavelength, the more intense the energy transmitted by the radiation.

- *UV-A* light (long-wave UV between 320 and 380 nanometers), often referred to as "black light," can be used to create interesting visual effects by causing certain materials to phosphoresce and fluoresce. This is the category of ultraviolet radiation that is used for medical therapies (discussed above), and seems to be the most active in human biochemistry.
- *UV-B* (medium wavelength between 280 and 320 nanometers) causes sunburn and skin cancer (with chronic exposure), and can damage the interior of the eye. UV-B is largely filtered out by the earth's atmosphere. Lamps producing UV-B are available only for medical use and from distributors approved by the U.S. Food and Drug Administration (FDA).
- *UV-C* (shortwave UV below 280 nanometers) is dangerous to people, but is useful in killing bacteria. It is almost entirely filtered out by the ozone in the upper atmosphere. UV-C lamps are used for germicidal air purification in hospitals and air-conditioning systems, disinfection of water and wastewater, and other anti-microbial processes.

Research has shown that the human body requires a small amount of UV-A radiation to produce vitamin D. As such, full-spectrum lamps specifically designed to radiate UV-A in similar proportions to noon sunlight can be used in rare applications where humans are totally deprived of natural light, such as during extended work in submarines or during arctic winters. However, except for these "clinical" applications, lamps designed to produce more ultraviolet should be avoided. As a rule for general illumination, every additional photon of ultraviolet radiation should be considered potentially damaging and avoided.

Some lamps produce levels of UV emission that are higher than the standards recommended by the International Radiation Protection Association or the FDA. Depending on the manufacturer and product, these may include high-output and very high-output fluorescent lamps, bare metal halide lamps, and halogen lamps. Specifiers should carefully follow manufacturers' recommendations for shielding, distance from the source, and maximum illuminance. An acrylic or tempered-glass UV lens can reduce the UV to safe levels, so that even a sensitive individual could safely receive eight hours of continuous exposure (Borg 1993).

Glass filters out some percentage of the UV content of daylight. The exact percentage varies with the type and thickness of glass. Most plastic glazing materials include UV inhibitors to reduce UV degradation of the material over time. Thus, the amount of UV transmitted through plastics is also a function of the specific chemical formulation of the material, and may vary with age or time exposed to sunlight. Also, UV radiation degrades quickly upon each "bounce" off of most reflective surfaces. Thus, indirect lighting systems also serve to reduce any UV content of light.

2.2.8 Other Forms of Radiation

Both electric light and daylight include other forms of radiation outside of the visible spectrum, including electromagnetic fields, radio waves, and X-ray or nuclear radiation. In most cases, these are trace amounts, and vastly less than from other common sources, such as household appliances. The various types are discussed below.

Electromagnetic field (EMF) radiation has been under investigation as a possible cause of leukemia and other cancers. Conventional 60-Hz fluorescent lamps and ballasts can radiate EMF similar to that in most other electrical appliances. However, EMF strength, measured in a unit called a milligauss, decreases dramatically as a geometric function of distance. The strongest exposure is generally from appliances within 6 to 12 inches of a person. Because electric lighting is typically overhead and at a greater distance from people, it is significantly less of a concern than numerous other appliances, such as electric blankets and hair dryers, which can be in close proximity to the user. Furthermore, recent improvements in lighting technology have generally reduced EMF emissions. For instance, electronic ballasts emit much less low-frequency EMF than older magnetic ballasts.

Epidemiological studies trying to show a correlation between exposure to EMF fields and cancer incidence have been contradictory and inconclusive. In 1998, after reviewing the status of current research, a panel of scientists at the National Institutes of Health cautiously voted by 67% majority to accept the position that electromagnetic fields should continue to be “regarded as a possible human carcinogen” in order to fund additional research (Utility Industry Business News 1998). Current research is shifting to investigating EMF as a potential endocrine disrupter, via impacts on melatonin synthesis and other hormones. A recent study that tested subjects' melatonin levels at night while exposed to EMF fields, found that the absolute level of exposure to EMFs was less important than the sequence of exposure: that fluctuating fields seemed to have a stronger negative effect (Raloff 1998b). Thus, power surges through household wires and electrical transients caused by intermittent use of electrical equipment close to a sleeping person would likely be of far greater concern than lighting equipment.

Other forms of emissions from electric lighting sources include low-level signals of ultrasound and radio frequency (RF). The U.S. Federal Communications Commission is responsible for regulating these emissions levels, particularly from electronic ballasts. Ultrasonic motion detectors must comply with these standards (see section 8.3). Some induction-type lamps have significant RF emissions that must be controlled with protective devices (see section 6.5.8 for a discussion of induction lamp technology).

Radioactive radiation from electric lights is less than from the natural background levels typically encountered. Some compact fluorescent lamps contain a minute amount (~1 billionth of a curie) of radioactive krypton or promethium. Even in the most improbable scenario, human exposure to this amount of radioactive material is harmless. To take an extreme example, if over an 8-hour period a person were to breathe the air in a small room in which all the radioactive krypton from a broken compact fluorescent was evenly distributed, the exposure would be approximately a thousand times less than the background radiation to which we all are exposed each day (Competitek 1988).

2.3 Light and Productivity

Lighting designers and industry advocates argue that good lighting results in productivity benefits for the business owner, and economic analysis shows that just a tiny improvement in worker productivity far outweighs the cost of an enhanced lighting system.

A recent study found that corporate CEOs and facility managers clearly value good lighting as a factor contributing to a quality workplace and are eager to receive objective proof showing a link to productivity (Ducker Research 1999). Until such hard evidence is available, the CEOs interviewed in this study were willing to accept worker satisfaction as an indicator of lighting and workplace quality.

Thus, the lighting industry has been on a quest to identify the attributes of "better" lighting that might be associated with enhanced performance. The formation of two committees, IESNA’s Quality of the Visual Environment and International Association of Lighting Designers' (IALD) Metrics of Visual Quality, have helped to speed this discussion, and resulted in the inclusion of the lighting quality based procedure in the *IESNA Lighting Handbook* (discussed in section 4.3 of the *Advanced Lighting Guidelines*). Similarly, a number of researchers have been searching to identify the most effective metrics by which to identify "better" lighting.[1] However, there has been only very modest success to

[1] In 1999, a group of industry and government organizations, named the “LightRight Consortium,” joined to fund a research agenda looking into the effects of lighting quality on office worker performance. The Ducker Research quoted above was the first phase of that effort.

date in identifying clear performance consequences for any specific lighting characteristics (Veitch 2000).

2.3.1 Recent Findings

The most definitive work to date relating lighting quality to office worker performance shows a clear improvement in clerical task performance between installations with electronic ballasts over installations with magnetic ballasts (Veitch and Newsham 1998; see sidebar Electronic Ballasts Improve Office Worker Performance). However, the same study could not find a significant effect on worker performance by varying the types of luminaires—parabolic louvered luminaires, prismatic lensed luminaires and direct-indirect luminaires. A similar but separate study, holding visibility of the task constant, also did not find an effect from different light distribution strategies on worker performance (Eklund 2000). Another set of researchers attempted to define the range of uniformity or non-uniformity in horizontal illumination of a workspace that would contribute to better performance. They looked at a very wide range of conditions and could not find a significant difference in performance.

There is a wide range in individual preferences for illumination levels and lighting conditions. One study that allowed office workers to set their own vertical and horizontal illumination levels with dimmers found that two-thirds of the population (the standard deviation) chose illumination levels +/-36% from the mean for horizontal illumination and +/-31% for vertical illumination. The minimum and maximum settings for the most extreme individuals had an even greater range, more like +/-70% (Veitch and Newsham 1999).

Given the range of individual preferences for illumination levels, it has been hypothesized that giving individuals the opportunity to control their own lighting will contribute to increased productivity. The two researchers who have studied this found that people do very much like to control their own lights, and indeed, such control results in measurable energy savings. But they could not find any improved performance that could be attributed to having individual control (Boyce et al. 2000; Veitch in press).

There's No Such Thing as the Hawthorne Effect

Many facility managers, when promoting the benefits of improved lighting to their bosses, are frustrated when faced with a quick dismissal that everyone knows that the “Hawthorne Effect" has already showed that lighting has no significant effect on worker performance. The popular interpretation of the Hawthorne Effect is that it is only management attention to employees, not physical working conditions, that has a measurable effect on employee productivity.

From 1927 to 1932 a series of experiments, involving only five women and varying work conditions, were conducted at the electronics assembly plant of Western Electric Company in Hawthorne, Massachusetts. Conclusions from these experiments are a favorite story told in lecture halls at most MBA programs around the country and have become embedded in popular business culture as the "Hawthorne Effect." Many business managers, having heard these stories, became convinced that physical working conditions, especially lighting quality, were insignificant in determining worker productivity. The problem is that the stories, as passed down over the years, are far from correct.

"The enduring mythology of the Hawthorne effect comes partly because the original researchers never published either a detailed discussion of the lighting tests or an analysis of the results. ‘Knowledge’ about them exists primarily as often-repeated anecdotes, which the archival records, as well as a few recent technical studies, completely undercut."—Joseph Romm (1999, p 223)

Joseph Romm, a writer interested in the effect of lighting on worker productivity, recently went back to the original documents and interviews with participants to sort things out. To set the record straight he wrote a detailed appendix about the Hawthorne Experiment for his book *Cool Companies*. From his analysis, he concluded that these early experiments with worker productivity were deeply flawed. For example, the study did not account for the presence of daylight, a mid-course change in two of the five test subjects, or a tracking and incentive system that gave the workers direct feedback on how they were doing. He makes a persuasive case that all subsequent (mis)interpretations were largely based on the biases and motivations of the researchers.

Electronic Ballasts Improve Office Worker Performance

"The good news for energy conservation is this: We found no support for the fear that as LPD [lighting power density] declines, so does lighting quality. There was no overall main effect of LPD in which performance, satisfaction, or mood was worse for the lowest LPD condition. Moreover, a clear pattern of evidence supports the adoption of energy-efficient electronic ballasts because of their effects on people." — researchers Jennifer Veitch and Guy Newsham (1998).

Veitch and Newsham tested nine different lighting installations for impacts on office worker performance on a variety of tasks, and also tested for changes in mood, health, satisfaction and comfort. They did indeed find positive effects, ranging in size from 1% to 25%, for many of their tests. However, due to the complexity of the variables and the sometimes contradictory findings, it is difficult to draw clear conclusions about which lighting system might be the best choice for office work in general. In spite of the complexity of the study findings, Newsham and Veitch were able to draw three very certain conclusions:

- Changes in lighting conditions can directly affect office worker performance
- Lighting power density is NOT a determinant of performance
- Electronic ballasts clearly improve office worker performance over magnetic ballasts

2.3.2 Observations on the Research

People can work successfully (at least for a short time period) under a wide range of illumination conditions and there is a very wide range of individual preferences. This is certainly consistent with the adaptability of the eye and the human visual system. Humans have evolved to function on a planet that varies from pitch black to 10,000 fc on a daily basis, with all conditions in between. Our primitive ancestors learned to live and work by firelight along with working in the full noonday sun. So it is logical that humans should not be highly optimized for one narrow condition.

Yet the question remains, how do we tell if one lighting condition is better than another? Perhaps we have not yet identified the correct descriptors of a "better" lighting environment. In one of the studies cited above, the primary variables are task illumination levels, lighting power density and luminaire distribution. However, the most significant findings compared worker performance under magnetic versus electronic ballasts. This implies that there was some stroboscopic or electromagnetic effect that was not an intended focus of the study, but was more powerful than the illumination characteristics that were under consideration.

Alternatively, productivity relationships may be more long term and thus would not be captured by short-term experiments. Since people are so highly adaptable, they can easily adapt to almost any test condition for a few hours or a day, especially as part of an experiment. Largely due to the expense of this type of research, very few researchers have been able to conduct experiments that look at truly sustained performance—over the course of weeks or months—or examine more realistic work conditions outside of the highly controlled laboratory. It is possible that the effects of "better" lighting only manifest themselves under the murky, tumultuous conditions of the real world.

Productivity Benefits

Lighting system improvements that increase worker productivity can yield a high return on investment. Consider, for instance, the cost associated with an employee. Assume that the direct costs of the employee, including wages, taxes and benefits, are $50,000 per year. This means that the employee is paid approximately $24 per hour, based on 40 hours per week and 52 weeks per year. Normal lost time due to holidays, vacations and sick time are part of the benefits.

A typical office worker requires about 100 ft² of dedicated space, mostly actual work area and access to it. Modern lighting systems consuming energy at the rate of 1.2 W/ft², operating 3500 hours per year (work time plus cleaning and other non-working hours) cost about $35 per worker per year to operate, including energy and maintenance. The annualized owning cost for a typical office lighting system costing about $2.50 per square foot is about $30 per year. In other words, the total cost of owning and operating the lighting system is about $65 per employee per year, or the same as about 2.7 hours of employee labor cost, or about 1/10 of 1% of annual productive work hours.

Based on these values, an improvement to an ordinary lighting system that improved employee productivity is very quickly amortized. For example, a 1% improvement in productivity throughout the year would realize a benefit to the employer worth $500. Investing $500 per employee in improved lighting, if it provided that small increase in productivity, would produce a 100% return on investment forever. A more modest investment of about $250 per employee would return 200% forever. For reference, a good office chair costs over $500.

The potential return on investment is staggering for basic lighting systems. Doubling the cost of typical lighting systems (adding about $250 per worker) enables the designer to employ dimming controls and to utilize better performing and more attractive design options that prevent bad lighting and have the potential to achieve good lighting. Tripling the cost of lighting systems (adding about $500 per worker) assures that a state-of-the-art lighting system complete with full control capability can be provided, assuming proper and responsible design.

2.3.3 Daylighting Studies

Two recent studies on daylighting in retail stores and schools were able to look at long-term effects under field conditions. The productivity indicators were annual sales data in the case of a chain retailer and standardized test scores in the case of three elementary school districts. Controlling for a wide range of other demographic and physical variables, much like a medical epidemiological study on the relationship of smoking and cancer, both studies found significant productivity effects associated with the presence of daylight (Heschong Mahone Group 1999).

Many researchers have confirmed that people consistently prefer having natural light and windows in their workspace, and that they also believe that the presence of windows or natural light contributes to enhanced productivity. While these beliefs are widely held, it has been notoriously difficult to isolate the multitude of variables that might be involved in order to identify a potential effect. Windows and natural light are inherently highly variable and present a very complex set of issues to consider, such as variation in illumination level over both time and space, glare, view, ventilation and psychological status. By looking instead at skylights, these two studies suggest that there may indeed be a natural daylight effect, independent of the many other qualities typically associated with daylight from windows.

In the first study, a chain retailer who operated a large number of similar stores, both with and without skylights, was found to have significantly higher yearly sales in the stores that had extensive daylight provided by the skylights. In a companion study, the standardized reading and math test scores for elementary school children were compared within three large school districts. In all three districts it was found that the children who spent the year in classrooms with the most daylight available from either skylights or windows were either learning significantly faster, or testing higher on math and reading tests, than children in classrooms without any daylight.

The explanation for these findings might be as simple as the addition of daylight providing higher levels of illumination in the spaces, or may involve some more complex visual, emotional or health effect yet to be sorted out. The studies remain highly suggestive, and it is hoped that future studies will be able to replicate the findings and perhaps start to identify specific mechanisms.

With these daylighting studies we have an example of a strong, organizational level productivity effect, which appears to be associated with illumination conditions.

3. LIGHTING IMPACTS AND POLICIES

Lighting has considerable impact on the environment. It is one of the major energy end uses in buildings and exterior applications. The production of electricity needed for lighting consumes fossil fuels, which contribute to air and water pollution. Furthermore, some lighting equipment is fairly short lived and lighting equipment and components create a continuous waste stream, as raw materials are extracted from the earth, delivered to factories, made into lighting equipment, installed in buildings, and finally removed and disposed of. Section 3.1 and 3.2 discuss lighting's energy and environmental impacts, respectively.

The importance of lighting to our livelihood and its impact on the environment has resulted in diverse and overlapping policies, regulations, and standards. Section 3.3, Lighting Policies, Codes and Standards, discusses these various policies and standards, including the IESNA recommended practices and standards.

3.1 Energy Impacts

Since its invention slightly over a century ago, electric lighting very quickly became the norm in this country. However, we shouldn't forget that not all lighting is provided by electricity. Daylighting uses none. Many remote locations in the United States and much of the developing world still use vastly inefficient fuel sources. Compared to the candles, kerosene lanterns or whale oil lamps that dominated the nineteenth century, electric lighting has offered huge improvements in cleanliness, reliability, economy and efficiency.

Where light was once considered a nighttime supplement to daylight, now it has become the norm for all our workplaces. Its use has vastly expanded the range and time of human activities. We can now operate our workplaces 24 hours a day. Arctic locations can operate through the winter. Huge buildings can be created without being limited in dimension by access to daylight. Enclosed spaces like ships and airplanes can operate in a healthy environment.

With this expansion of uses, lighting energy use has become one of the major uses of energy in the country. While efficiencies have improved dramatically, the use of electric lighting has also increased. Currently, buildings consume over one-third of all sources of energy use in the United States (Interlaboratory Working Group 1997, 1.5) and electricity accounts for almost 80% of the cost of that building energy consumption (3.20). Overall, lighting is estimated to account for 23% of national electricity consumption. Of national lighting energy use, residential lighting is estimated to constitute about 20%; commercial lighting, 60%; industrial 16%; and street lighting and other uses, 4% (Atkinson et al. 1995, p 399-427). The *Advanced Lighting Guidelines* focuses on the commercial[1] lighting segment, which was estimated to consume 4 quads (365 billion kilowatt-hours) of energy in 1997 (Interlaboratory Working Group 1997, p 3.9).

These numbers are substantial, but only begin to describe the impacts of lighting energy use. In addition to the direct energy used for lighting, there are other secondary effects. For example, all of the electricity used for lighting eventually turns into heat, which is usually unwanted in commercial buildings. Because of heat from internal sources such as lights, equipment and people, most commercial buildings in the continental United States require some cooling even in the coldest months of the winter. This excess heat must be removed from buildings via air conditioning. The additional air-conditioning load created by electric lighting can add another 20% to the electricity use attributable to electric lighting.[2]

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[1] The term "commercial" is used throughout to designate all non-residential building uses in general, not just those involved in commerce.

[2] The degree of this effect is of course determined by both the specifics of each building's design and operation, and its local climate. See Rundquist et al. 1993.

Lighting use has substantial impacts on our electric generation systems. The majority of commercial lighting use, and the associated added cooling loads, occur during periods of peak electricity demand, and thus directly impact the need for additional generation and distribution facilities. Furthermore, electricity used at a building site requires about three times as much energy consumption back at a fossil fuel power plant. Thus, there is a substantial multiplier effect for each kilowatt used at a building site, if we consider the total amount of energy consumed by lighting, including that needed to generate it and transmit it from the power plant.

These energy impacts help to explain why lighting efficiency is so important. Efficiency improvements in lighting technologies and practice have been dramatic in the past few decades. Indeed, in California, with its aggressive energy-efficiency programs during the past decade, 75% of all building energy savings have been found attributable to lighting efficiency measures (RLW 1999). In 1997 the National Laboratories estimated that current national lighting energy can be reduced by 50% by the year 2020, while simultaneously improving lighting quality (Interlaboratory Working Group 1997). The same year, a study in California showed that if the most efficient lighting technologies then commercially available were applied throughout the new and existing building stock, commercial lighting energy savings for the state could total up to 7500 gigawatt-hours per year in 2010. This is roughly equivalent to the annual output of one entire nuclear power plant.

The drive toward greater lighting system efficiency has been one of the principal motivators for recent changes and improvements in lighting technology. Opportunities for more efficient electric lighting sources, more effective design strategies, greater use of daylight, and use of controls to eliminate unneeded light all promise substantial reductions in commercial lighting energy use in the future.

3.1.1 Lighting Energy Use by Building Type

Facility managers, energy service companies, and government program managers need to know where to target their efforts to achieve the greatest improvement in lighting efficiency for the least effort. It's helpful for lighting program managers and others to understand which building types use the most lighting energy and where the greatest savings might be achieved with energy efficiency improvements. Figure 3-1 shows estimated national lighting energy use by building type.

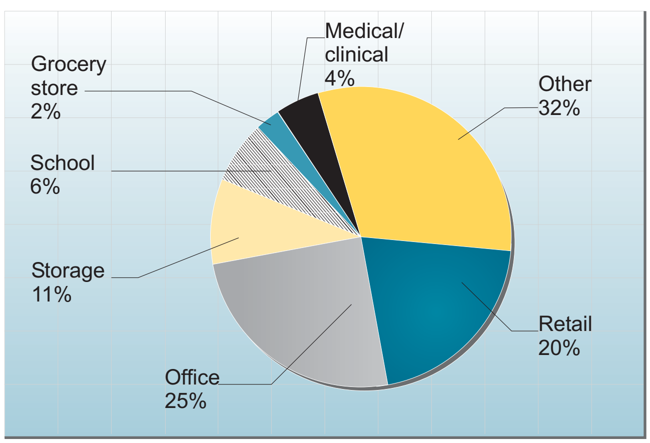

Figure 3-1 – National Lighting Energy Use by Building Type
Source: Lighting Source Book, Lawrence Berkeley National Laboratory 1997

Figure 3-1 is based on national commercial lighting energy use patterns researched by Lawrence Berkeley National Laboratory (1992; 1997). While the researchers carefully analyzed the best data available at the time, they were still forced to rely on considerable interpretation and educated guesses, given the lack of detail that was available on the national level. National data is rapidly aging, especially considering the rapid technological changes in the lighting industry. A number of studies are underway to update national patterns of lighting energy use for different commercial building types for different regions, but as of this edition of the *Advanced Lighting Guidelines*, none were complete.

More complete data on energy use by building type is available for California as a result of utility company research on the effects of their efficiency programs. California is probably the most studied lighting market in the country, with seven major lighting studies conducted between 1994 and 1998 (Xenergy 1999). As a result, extremely reliable data is available on patterns of lighting energy use in California buildings. Some of this information may apply to buildings in other parts of the nation, but in general, California buildings are believed to be substantially more efficient than buildings in other states, and the data should be used with caution if applied elsewhere.[1] California has had an aggressive building energy code for over 20 years. In addition, the energy code has been reinforced since the mid-1980s by utility programs that specifically reward projects that surpass code requirements. Working together, the code and the utility programs have helped to create a large population of relatively efficient buildings.

The detail on lighting energy use patterns by building type reported here is interesting in and of itself, but also as a study of how building energy efficiency can improve over time. The average lighting power density for existing commercial buildings in 1994 was 1.48 W/ft² (HMG 1997) while the average for newly constructed buildings in 1998 had dropped to 1.22 W/ft² (RLW 1999).

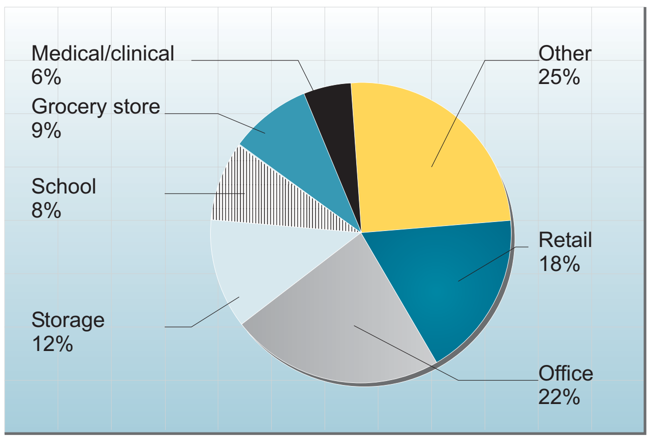

Figure 3-2 – Commercial Lighting Energy Use in California, 1994, by Building Type
Source: Heschong Mahone Group, Lighting Efficiency Technology Report, Vol. 1, Baseline 1997.

Figure 3-2 shows the distribution of lighting energy use by existing California commercial buildings in 1994. Here, large offices and retail buildings have by far the greatest share of lighting energy use. (The miscellaneous category includes a wide variety of buildings, which did not fit into the other definitions.) Looking instead at the lighting energy use of newly constructed buildings, in Figure 3-3, retail and wholesale stores and offices assume even more importance.

[1] A recent review of all efficiency efforts in California by the RAND corporation found that 3% of the current economic growth in California is attributable to energy efficiency improvements over the past twenty years. (Bernstein et al. 2000).

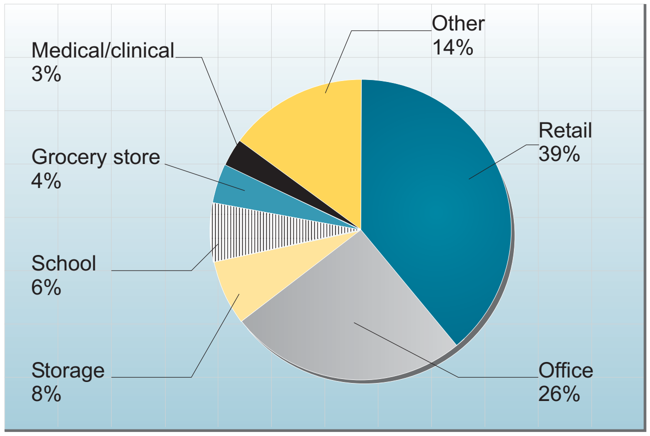

Figure 3-3 – New Construction Commercial Lighting Energy Use in CA, 1998, by Bldg Type
Source: RLW Analytics, Nonresidential New Construction Baseline Study, July 1999

Figure 3-3 shows the relative proportion of lighting energy use consumed by recently constructed buildings in California. New construction projects tend to have more efficient lighting systems than the existing building stock. The types of buildings also vary in their relative proportion, as the construction industry responds to the market. Often there will be a surge in one building type for a few years until that type is over built, and then another type will receive the attention of the construction industry. This shift in construction patterns shifts the relative impact of different building types.

In this case, for new buildings, retail and wholesale stores were found to consume the largest portion—39% of the state total of lighting energy (these numbers are for interior commercial lighting only). Offices are the next largest consumer of lighting energy, at 26% of the state total. These numbers are a function of three variables: the relative efficiency of the lighting systems in these building types, the hours of operation of the lighting systems, and the overall square footage of that building type recently constructed in the state. Thus, while square footage of new offices in the state (31% of all commercial building area) is larger than retail and wholesale stores (22%), stores have less efficient lighting systems and longer hours of operation than offices, making the energy impact of retail stores larger. The “other” category includes eight other building types that each represent 1% or less of lighting energy use by new buildings.

The results of these various studies may seem inconsistent. It should be cautioned that in comparing findings between different studies of lighting energy use, one should be careful to compare baseline assumptions and methods of data collection. For example, some studies may include only ceiling-mounted luminaires, while others report on all sources of lighting, including furniture-mounted task lamps and plug-in lamps. The most reliable data comes from detailed on-site audits of a scientifically sampled building population, as opposed to surveys of owners or pooled data from energy audits.

3.1.2 Lighting Energy Use as a Percentage of Whole Building Energy Use

Another view of lighting energy use is how important it is to a given building owner. A study for the California Energy Commission (1990) estimated lighting energy use constituted 42% of all commercial electric energy use in the state. Since then, in a very careful study of newly constructed buildings in California, 29% of statewide electrical energy use was found to be consumed by interior lighting. This is considerably less than the previous estimate, probably because lighting efficiencies have increased dramatically in recent years relative to other electric energy uses.

Average numbers for all buildings only give part of the picture. It is often more informative to look at lighting as a percentage of building energy use by specific building type, as in Figure 3-4. Here, grocery stores show only 17% of their electrical energy devoted to lighting, since they are big users of refrigeration and cooling. Other building types have a relatively high percentage of lighting energy use, such as libraries, gymnasiums, and education facilities (37% to 43%), largely because they have so few other demands for electrical energy. Once again, retail and wholesale stores show up as having significant use of lighting energy relative to their overall electric bills. For these building types, a lighting efficiency improvement will have a big effect on the owner's total utility bill.

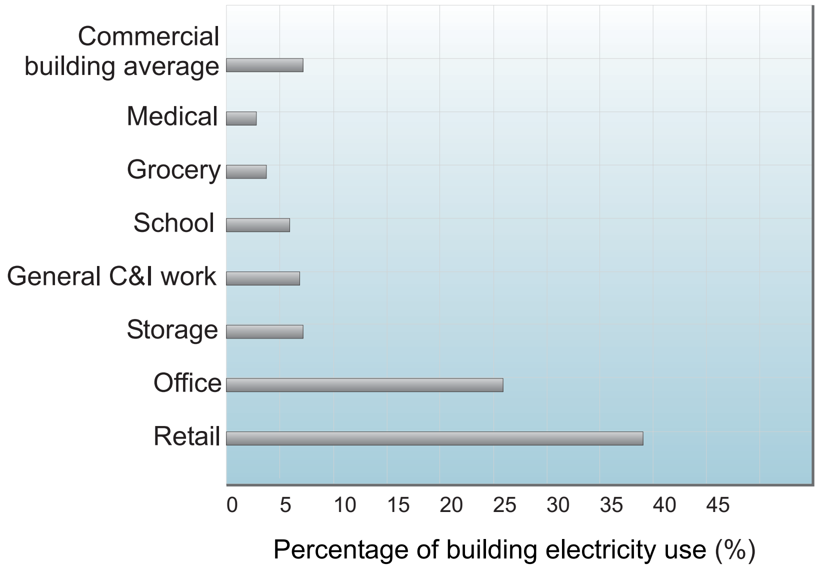

Figure 3-4 – % of Building Electricity Use Devoted to Lighting, CA New Construction, 1998
Source: RLW Analytics, Nonresidential New Construction Baseline Study, July 1999

When the information for newly constructed buildings in California is sorted by energy use intensity, as in Figure 3-5, it is clear that grocery stores have the most intensive use of lighting energy overall, as measured in kilowatt-hours per square foot per year (kWh/ft²·yr). Here graphs present just a sampling of building types. Refer to the original source for information on more building types.

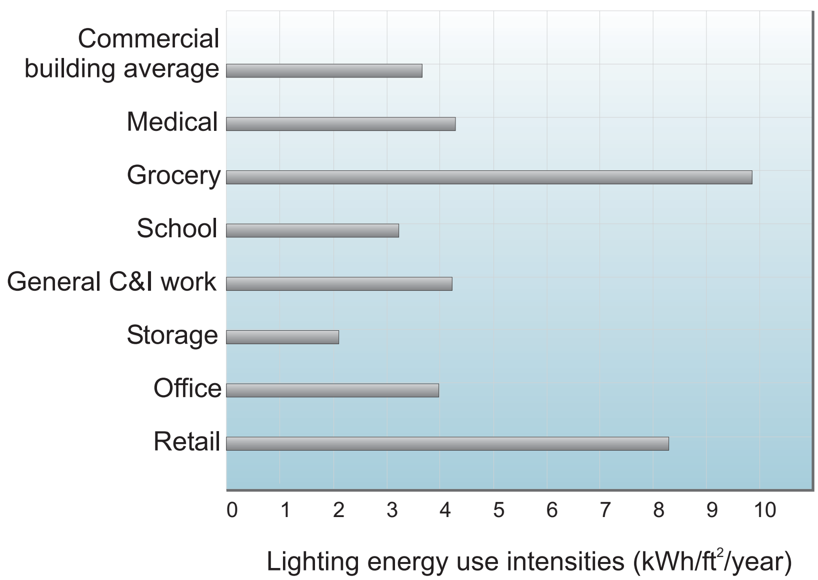

Figure 3-5 – Lighting Energy Use Intensities, by Building Type, CA New Construction, 1999
Source: RLW Analytics, Nonresidential New Construction Baseline Study, July 1999

Figure 3-5 shows that the average *new* commercial building in California uses 4.75 kWh/ft² per year to light its interior spaces. This ranges from a low of 2.12 kWh/ft² per year for commercial and industrial storage spaces to a high of 9.87 kWh/ft² per year for grocery stores. While the majority of commercial building types are using from 3 to 5 kWh/ft² per year, restaurants, retail and wholesale stores, and grocery stores are all at the high end of lighting energy intensity, from 7 to 10 kWh/ft². This is another good indicator that they are more likely to benefit from significant savings that could result from lighting efficiency measures, such as more efficient equipment and/or greater use of daylighting controls or time-scheduling devices.

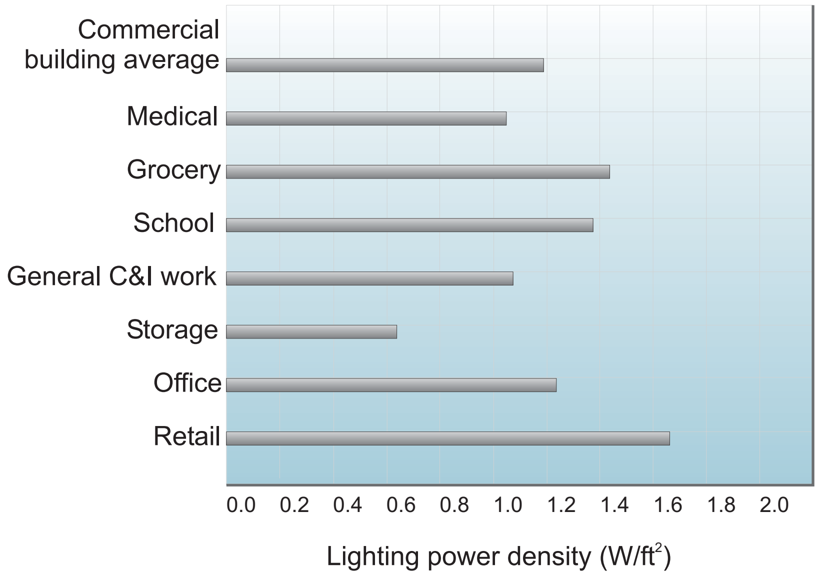

Figure 3-6 – Lighting Power Density by Building Type, California New Construction, 1998
Source: RLW Analytics, Nonresidential New Construction Baseline Study, July 1999

Figure 3-6 illustrates the current average lighting power density, in watts per square foot, for a selection of commercial building types in California (RLW 1999). These values are drawn from a statistically valid random sample of new buildings constructed between 1994 and 1998, and have been confirmed in a subsequent study to be highly accurate. It is interesting to note that each of these average lighting power densities for the building population are substantially less than the code allowances current at the time of construction.

3.1.3 Lighting Impacts on HVAC Systems

All forms of lighting add heat to a building. This heat can be useful when the building requires additional heat. However, most commercial buildings spend the majority of their operating time in cooling mode, where additional heat from lighting systems is a liability. This is because there is so much heat generated internally from lights, office equipment and people, and there is relatively little building skin area to lose this heat. Such buildings are “internal load-dominated.” Small commercial buildings, with a proportionately greater ratio of surface area exposed to the weather, can function more like residential buildings, where the building skin, or “envelope,” is responsible for most of the heating or cooling loads on the HVAC system. These buildings are “envelope-dominated.”

In internal load-dominated buildings, a reduction in lighting energy will also reduce HVAC energy use. Reduced lighting results in less heat production within the building, and thus a smaller cooling load. The impact of lighting energy use reductions on HVAC systems varies, by climate and by building design and operation. This is best assessed by monitoring existing buildings, or conducting computer energy modeling of proposed buildings. Table 3-1 estimates the range of magnitude of these effects for a sampling of different areas of the country. The warmest states, such as Florida and Louisiana, have the biggest reductions in cooling loads with a reduction in lighting energy use, on the order of 30% or more. The cooler states, such as Colorado, Michigan and Rhode Island, can have about a 20% increase in net heating load for those smaller buildings that are dominated by heat losses through their walls and roofs. However, the short heating season for commercial buildings, and the higher cost of electricity for cooling compared to the cost of heating fuels results in net cost savings for lighting reductions even in these cooler climates.

Table 3-1 – Typical Lighting Impacts on HVAC Use by Climate[1]
HVAC interaction with lighting savings

Location	Cooling loads	Heating Loads for Large Building	Heating Loads for Small Building
Phoenix, AZ	-30%	0%	0%
Los Angeles, CA	-23%	0%	0%
San Francisco, CA	-16%	1%	2%
Denver, CO	-16%	7%	22%
Tampa, FL	-33%	0%	0%
New Orleans, LA	-29%	1%	2%
Detroit, MI	-14%	8%	23%
Philadelphia, PA	-17%	6%	18%
Providence, RI	-13%	7%	22%
Knoxville, TN	-21%	4%	11%
Seattle, WA	-7%	4%	13%

Reduced lighting energy use can result from either a more efficient lighting system, or from better controls to decrease the hours of lighting use. With a more efficient system, less heat is added to the building per unit of useful light. With fewer hours of operation due to lighting controls, there's less time for the lights to contribute heat to the building. Lighting efficiency improvements work uniformly across all hours of operation to reduce overall lighting energy use. Controls, on the other hand, can differentially reduce lighting energy use during key periods of HVAC demand. Examples include photocontrols for daylighting systems or demand shedding systems. Such lighting control systems can have a proportionately bigger effect on HVAC energy cost per unit of energy savings, since energy prices are often higher during peak periods. Chapter 8 discusses lighting control systems in detail.

Another potentially important benefit of reducing lighting energy use is a reduction in the size of HVAC equipment. Installing more efficient lighting can reliably reduce the generation of heat within the building, often the size of the cooling plant required for the building can also be reduced. This can result in substantial first-cost savings for new construction projects or retrofit projects that involve upgrading the building's cooling system.

Unfortunately, the recent increase in lighting energy efficiency, which has reduced building heat loads, has been accompanied by a simultaneous increase in office equipment energy use, as companies install ever more copiers, computers, printers and other such equipment. Even though the efficiency of office equipment has also been improving, their growing numbers have tended to cause a steady increase in energy use overall by these systems.

3.1.4 Lighting Impacts on Peak Electric Loads

Commercial building lighting generally operates during the day and is strongly associated with the heaviest use periods of electricity, called the peak load period. For many utilities the peak electricity use period occurs during the late afternoon on hot, sunny summer days, which is also the time of peak cooling loads. Because most lighting is on during peak utility times, any reduction in lighting energy use is also likely to reduce peak demand by reducing both lighting energy use and cooling equipment energy use. This reduction in peak demand is one of the most important aspects of lighting energy efficiency, and has significant implications for both the building owner and the utility.

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[1] Values listed here use the tabulated numbers and calculation method described in Rundquist et al. 1993. Assumes new construction with a seasonal efficiency of .75 and MCOP of 0.24.

Many utilities have sizeable “demand charges” that are determined by electricity use during specifically defined peak periods. For example, in a utility district that has a demand charge of $10 for each peak kilowatt, a 100,000-ft² building that reduces its lighting energy use by 0.1 W/ft² would see a reduction of 10 kW in peak use, resulting in a savings of $100 per month on demand charges. The economic significance of such demand reductions is highly dependent on the local utility rate structure. Consult with your local utility representative for more information.

Managing peak demand is extremely important for the utility. Generating plants that operate during peak periods are typically more expensive to operate. In addition, peak load management can avoid the threat of system overload and brownouts, and can help utilities reduce their costs in serving customers. With reliably lower peak loads, a utility may be able to defer the need for building new power plants, which can be extremely expensive, or avoid purchasing power from other suppliers at the highest rates.

Figure 3-7 through Figure 3-13 illustrates the range of lighting schedules for different commercial building types. These graphs present generic schedules developed for representative buildings in California, simplified from more extensive monitored data. Classrooms for K-12 schools have their heaviest use during the daytime hours when school is in session. Offices show extended lighting use into the evening hours and for a portion of the weekend because some workers work late or on weekends. Retail buildings typically have the longest hours of lighting use, extending well into the night and continuing all of Saturday and Sunday.

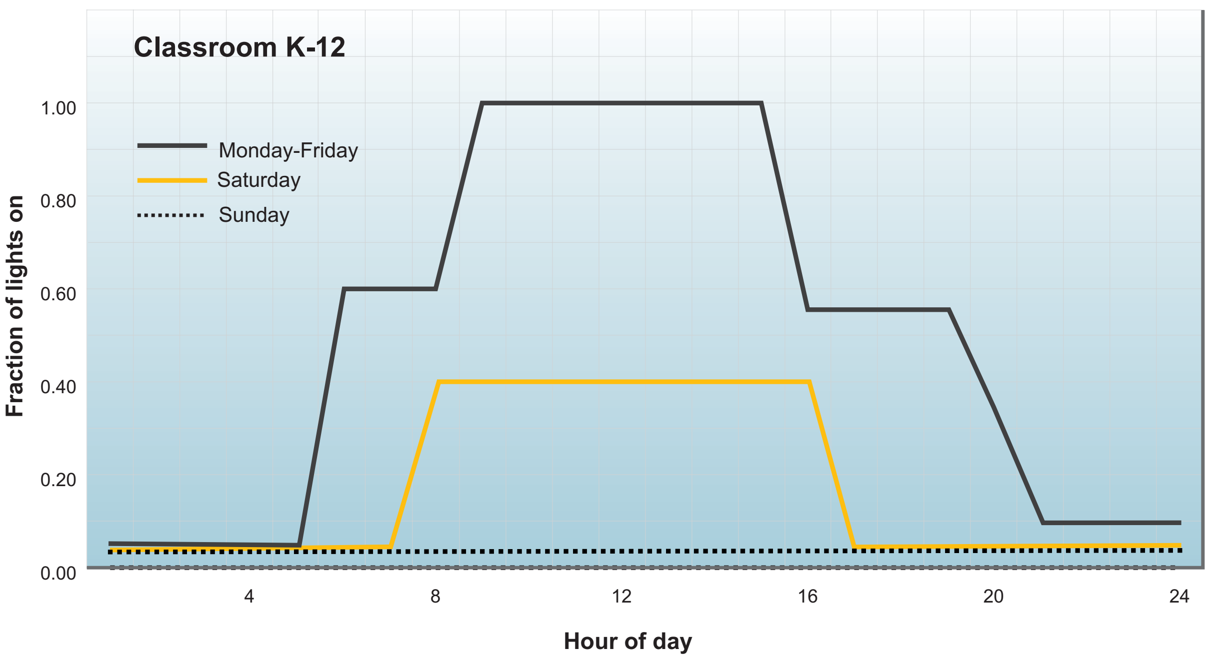

Figure 3-7 – Schedules for Lighting Use, K-12 Classroom
This lighting schedule is an average from a large set of monitored data collected by Southern California Edison for this building type

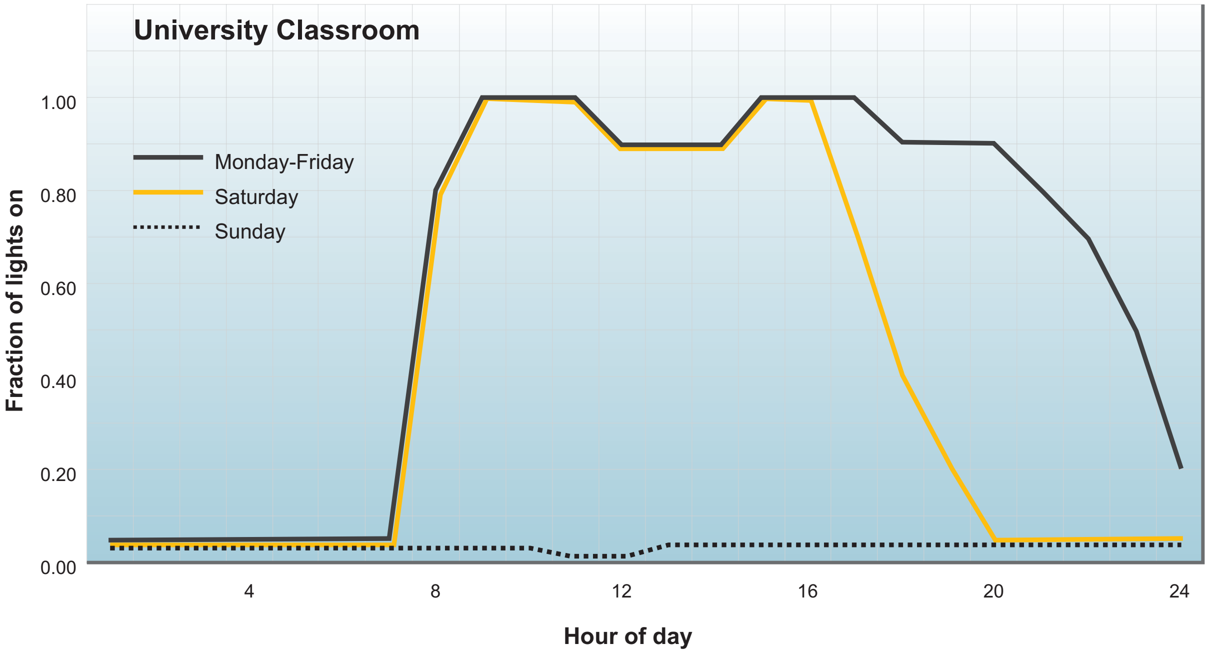

Figure 3-8 – Schedules for Lighting Use, University Classroom
This lighting schedule is an average from a large set of monitored data collected by Southern California Edison for this building type

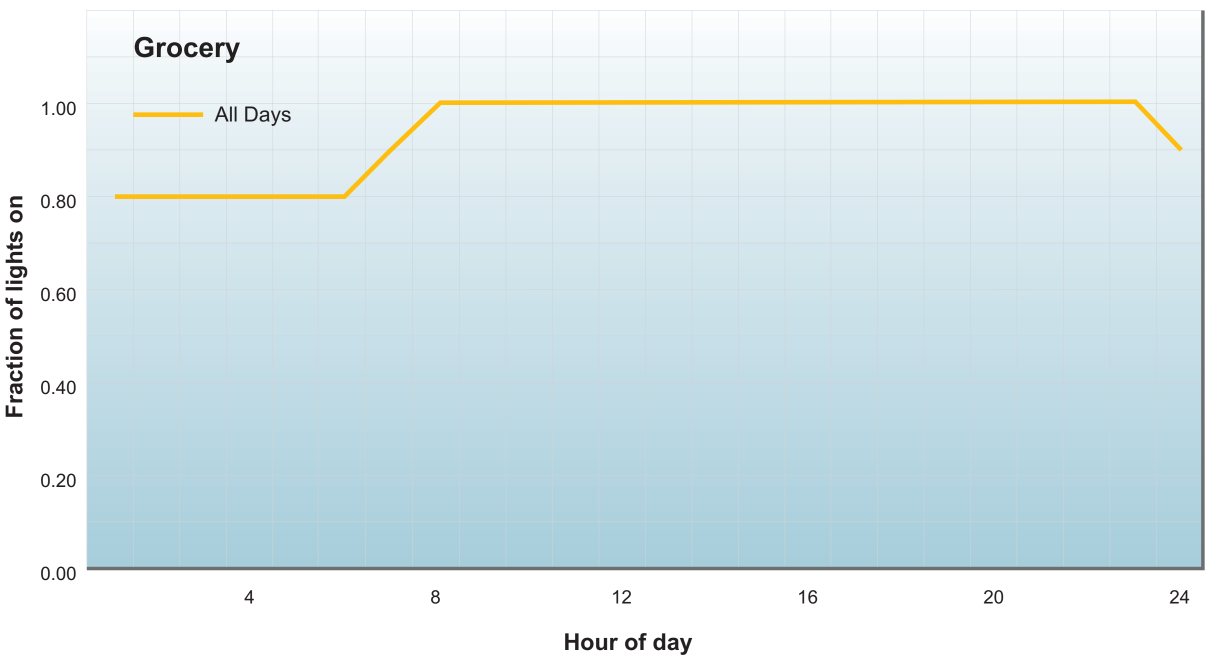

Figure 3-9 – Schedules for Lighting Use, Grocery
This lighting schedule is an average from a large set of monitored data collected by Southern California Edison for this building type

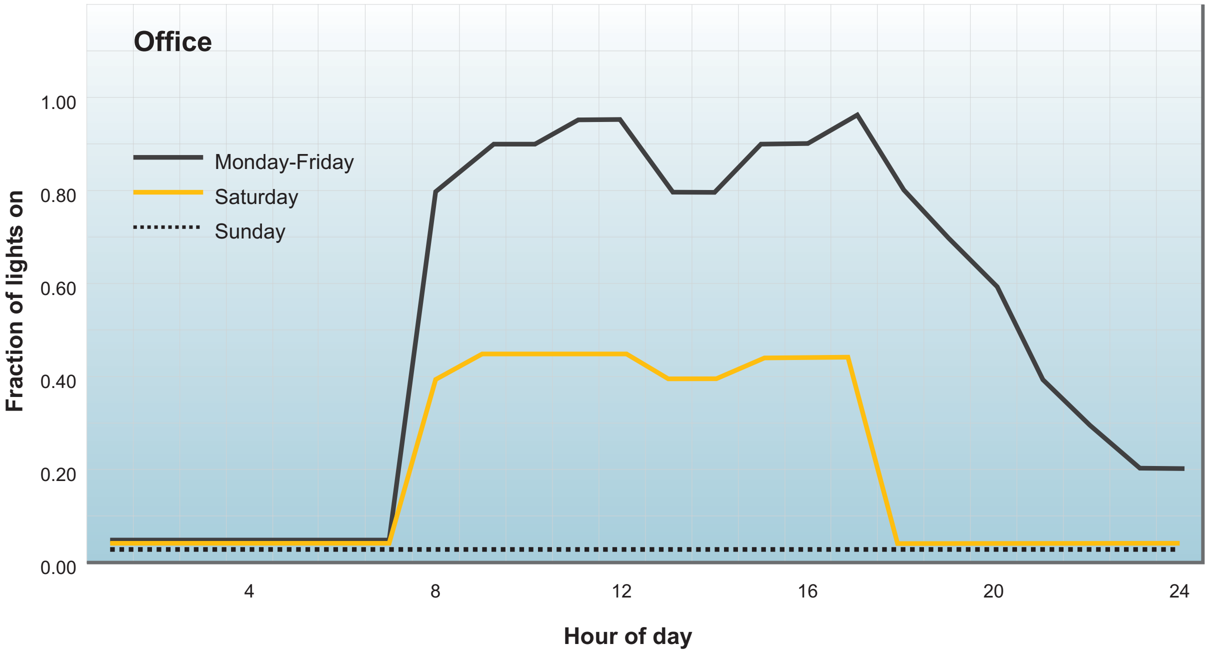

Figure 3-10 – Schedules for Lighting Use, Office
This lighting schedule is an average from a large set of monitored data collected by Southern California Edison for this building type

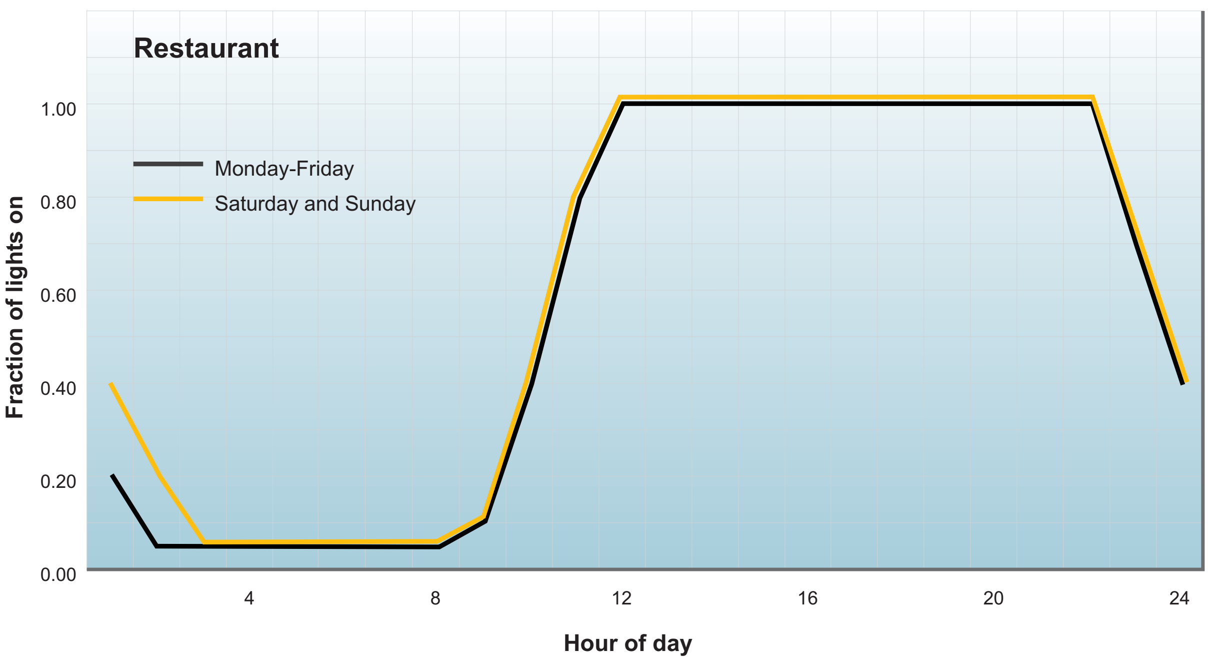

Figure 3-11 – Schedules for Lighting Use, Restaurant
This lighting schedule is an average from a large set of monitored data collected by Southern California Edison for this building type

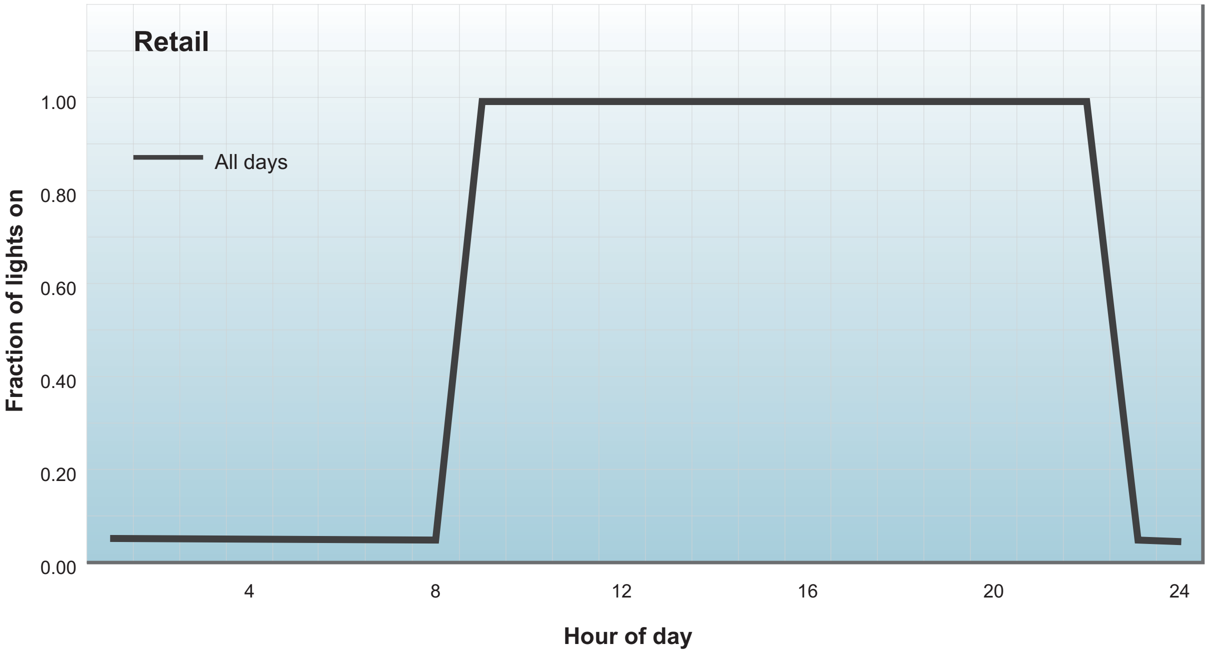

Figure 3-12 – Schedules for Lighting Use, Retail
This lighting schedule is an average from a large set of monitored data collected by Southern California Edison for this building type

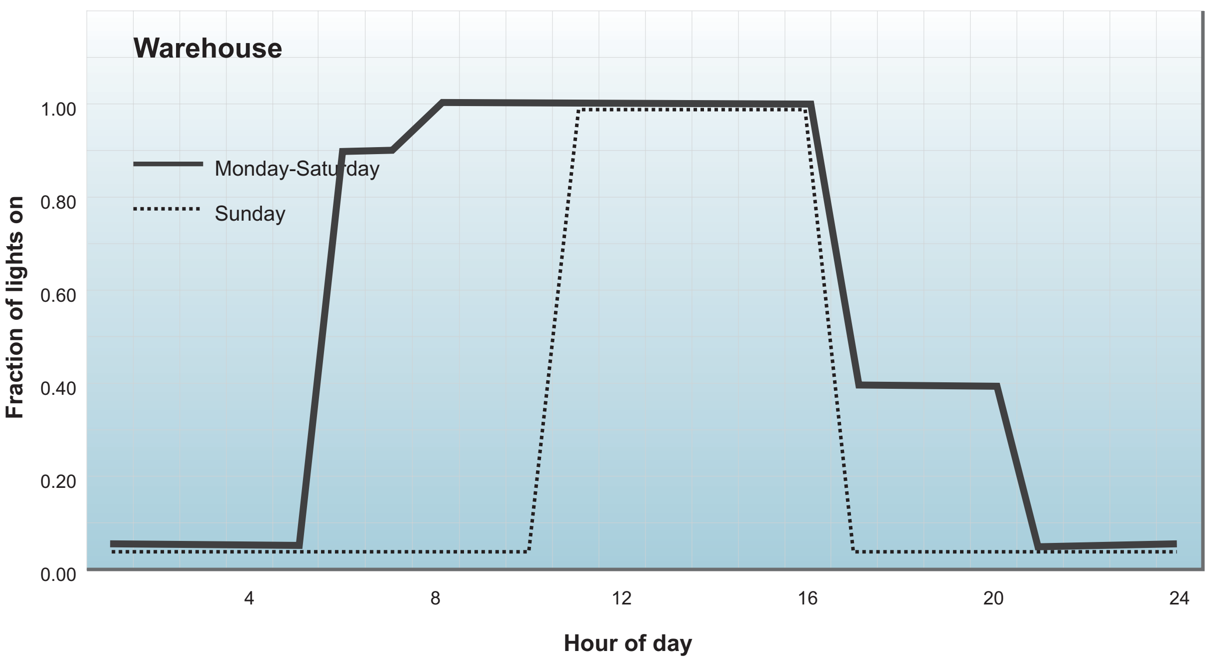

Figure 3-13 –Schedules for Lighting Use, Warehouse
This lighting schedule is an average from a large set of monitored data collected by Southern California Edison for this building type

Some lighting efficiency strategies are more effective at reducing peak load because of the way they affect these lighting energy use patterns. For example, a photocontrol system that turns off or dims the electric lights during daylight hours can dramatically reduce peak loads. A well-designed daylight system can provide more light with less heat gain than any of the most efficient electric lighting sources. Daylighting systems combining skylights with photocontrols have been shown to reduce peak building energy demand by 10% in Los Angeles.[1] Of course any peak demand reduction is highly dependant on the individual building design and local climate conditions. Energy analysis software can help predict these savings for different buildings (see section 4.4 for a discussion of energy analysis tools).

Another control strategy that results in reliable peak demand reduction is called “load shedding.” A whole-building monitoring system monitors electric power; if it approaches a predetermined limit, some of the building systems are shut down to temporarily reduce power. Dimmed lighting systems are a natural candidate for load shedding, if slight and temporary reductions in lighting levels do not adversely affect occupant productivity. Lighting level reductions of 10–15% will be unnoticeable to most occupants but may be sufficient to keep the building within its predetermined load limits. Such a load shedding system can either be designed to respond to the building owner's desire to avoid additional demand charges, or to the utility system's immediate need to avoid dangerously high system-wide peak demands that might threaten the system's reliability.[2] For more information about controls strategies for responding to emergency alerts from electric utilities, see section 8.1.5.

3.2 Environmental Impacts

There’s growing concern for reducing the environmental impacts of lighting energy use and understanding the environmental implications of our lighting system choices. Lighting use in commercial buildings has direct and indirect environmental consequences as a result of electricity generation, energy use and natural resource consumption during equipment manufacturing, and the disposal of used equipment. Lighting can also have very direct impacts on the social, physical and biological environment due to wasted light spilling out beyond its area of intended use. All of these impacts are discussed in the sections below.

3.2.1 Energy Impacts on the Environment

Electricity use for lighting has many environmental impacts apart from the consumption of nonrenewable resources. These impacts vary depending on how the electricity is generated. Coal-fired power plants are associated with air pollution and acid rain, and are also the largest source of air-born mercury emissions (EPA 1997). Hydropower plants can affect fish populations and the availability of water for farmers. Nuclear power plants have long-term disposal costs. Even renewable energy sources can have negative impacts, such as the interference of large wind turbines on bird migrations.

Every kilowatt-hour reduction in lighting energy use directly reduces these negative impacts of electricity use. Table 3-2 below delineates the sulfur dioxide, nitrogen oxide and carbon dioxide emissions of electricity generation by state. (See section 3.2.3 for a discussion of mercury emissions.) Missing information is indicated with a dash. These emissions are considered key "indicator" chemicals that negatively impact air quality, the production of acid rain, and global climate change.

Reducing the need for additional power plants has been one of the biggest motivations for utility programs that promote lighting energy efficiency. These are often called “demand-side management” programs because they act to balance power generation needs by reducing demand for electricity, as opposed to increasing electric generation supply. More people can be served with existing equipment if everyone uses electricity more efficiently. Fewer power plants mean less pollution and fewer sites that must be found that will tolerate the construction of a new power plant. During the 1980s, the construction of nuclear power plants in the United States became especially controversial and politically difficult. By the 1990s, no new nuclear power plants were planned anywhere in the nation.

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1 PG&E daylighting initiative case study of grocery store in Los Angeles, http://www.pge.com/pec/daylight.

2 During a recent test in California on a critical "power watch" day in September 2000, a voluntary reduction in lights and computer use at state buildings was seen to create 180 megawatts of peak load reduction, while a similar voluntary reduction in grocery store lighting contributed 100 megawatts in peak reduction. (Sacramento Bee article by Carrie Peyton, October 6, 2000.)

Table 3-2 – Air Pollution Impacts of Lighting Energy Use, by State
Source: U.S. EPA, http://www.epa.gov/airmarkets/egrid.

State	Sulfur Dioxide Emissions (lbs/kWh)	Nitrogen Oxides Emissions (lbs/kWh)	Carbon Dioxide Emissions (lbs/kWh)
Alaska	0.003	0.006	1.485
Arizona	--	--	--
Arkansas	0.004	0.004	1.447
California	0.000	0.002	0.669
Colorado	0.005	0.008	1.994
Connecticut	0.004	0.002	1.268
Delaware	0.013	0.005	1.821
DC	0.018	--	2.495
Florida	0.008	0.004	1.477
Georgia	0.010	0.004	1.566
Hawaii	0.006	0.004	1.920
Idaho	0.001	0.000	0.199
Illinois	0.010	0.005	1.145
Indiana	0.016	0.012	2.936
Iowa	0.010	0.009	2.086
Kansas	0.005	0.007	1.810
Kentucky	--	--	--
Louisiana	0.009	0.004	1.594
Maine	0.004	0.001	1.234
Maryland	0.011	0.006	1.794
Massachusetts	0.006	0.003	1.481
Michigan	0.007	0.006	1.551
Minnesota	0.004	0.007	1.778
Mississippi	--	--	--
Missouri	0.010	0.007	1.882
Montana	0.002	0.004	1.210
Nebraska	--	--	--
Nevada	0.004	0.006	1.732
N. H.	0.006	0.002	0.877
New Jersey	0.002	0.004	1.154
New Mexico	0.004	0.008	2.065
New York	0.004	0.002	0.914
North Carolina	0.008	0.004	1.327
North Dakota	--	--	--
Ohio	0.020	0.008	1.945
Oklahoma	0.005	0.006	1.831
Oregon	0.000	0.001	0.183
Pennsylvania	0.011	0.004	1.296
Rhode Island	0.000	0.004	1.047
South Carolina	0.006	0.003	0.899
South Dakota	0.003	0.003	0.562
Tennessee	0.011	0.005	1.306
Texas	0.003	0.005	1.592
Utah	0.002	0.006	2.066
Vermont	--	--	0.210
Virginia	0.006	0.003	1.238
Washington	0.001	0.001	0.260
West Virginia	0.019	0.007	1.865
Wisconsin	0.009	0.007	1.926

Distributed Power Generation

An alternative to large central power plants is distributed power generation from many small plants. Small gas-fired generators became very economical within the past decade, as the price of natural gas fell and the technology improved.[1] These conditions have increased the frequency of "co-generation" where a company generates some or all of its own electricity on-site. Co-generation has the added advantage that the waste heat from the small generator can be captured and used for water heating, space heating or process applications.

Solar Energy Sources

Photovoltaic (PV) cells provide another source of distributed electricity generation using clean solar energy. PV cells that generate electricity directly from solar energy can be mounted on a building's

[1] Recent increases in the price of natural gas may change this equation.

roof, walls or adjacent structure, but PV systems involve much more than the simple addition of cells to a roof. PV cells create direct current, which must be transformed into alternating current to operate standard building equipment. Storage batteries enable use of the electricity at a later time. PV systems are especially valuable in remote areas, where bringing in electricity from the utility grid is prohibitively expensive. They have also proven useful in smaller landscape and park lighting systems, where the daytime charge of electricity can supply nighttime needs for light.

Some electronic ballasts can operate on either direct or alternating current. Also, 12-volt DC systems for lighting, refrigerators and other uses are common in marine applications and are sometimes used in building applications. In the future, there may be less of a need to convert DC to AC, reducing cost, and making photovoltaic energy more cost effective for lighting and other applications.

The cleanest and most efficient use of the sun's energy is, of course, daylighting. Daylighting involves no generation impacts, no transmission losses, no conversion losses, and few incremental manufacturing impacts. Given that the majority of commercial building lighting use currently occurs during the daytime, a significant reduction in electricity use could be achieved with more widespread use of daylight in buildings carefully designed to optimize its use.

To demonstrate daylighting's potential, Figure 3-14 and Figure 3-15 estimate the floor space of existing commercial buildings that could take advantage of daylight[1]. It shows that for skylights or toplighting, 62% of the existing commercial building floor area is directly under a roof. In contrast, floor area that can easily be lit from windows or sidelighting represents only about 25% of the square footage. Thus, the current area available for top lighting is about 2.5 times as much as from sidelighting. In some areas of the country that favor low rise construction, the opportunity for toplighting is even larger.

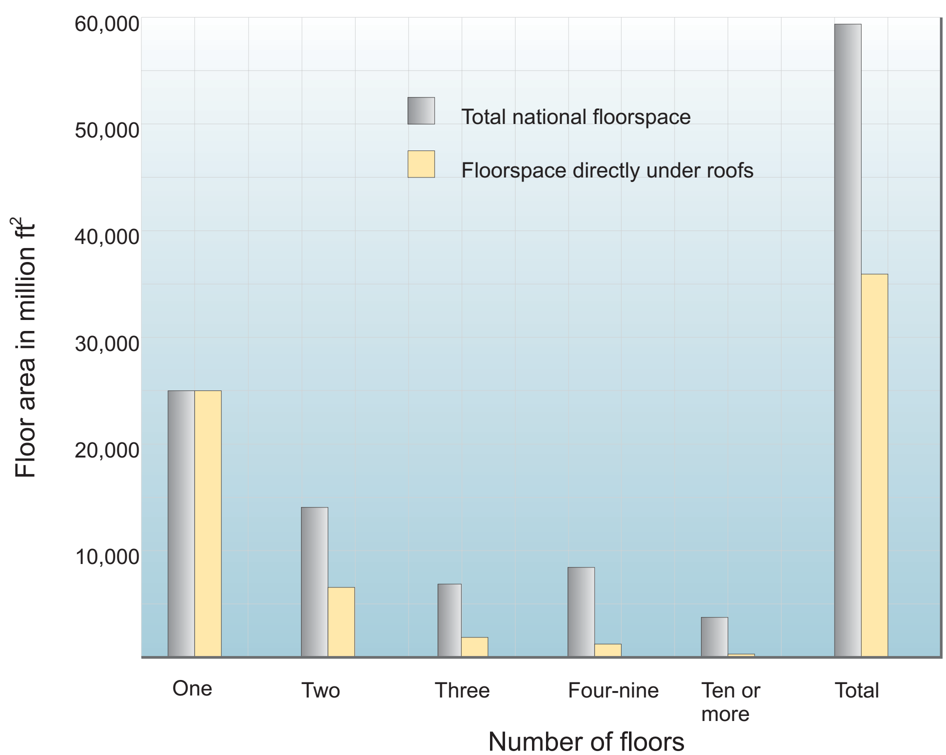

Figure 3-14 – Percentage of Commercial Floor Area Available for Daylighting by Toplighting
Source: Heschong Mahone Group, based on CBEC's 1998 data, U.S. EIA.

1 These estimates are based on national data from the Commercial Building and Energy Consumption Survey, 1988, of the U.S. Energy Information Agency, making assumptions about the general proportion of building perimeter relative to number of floors.

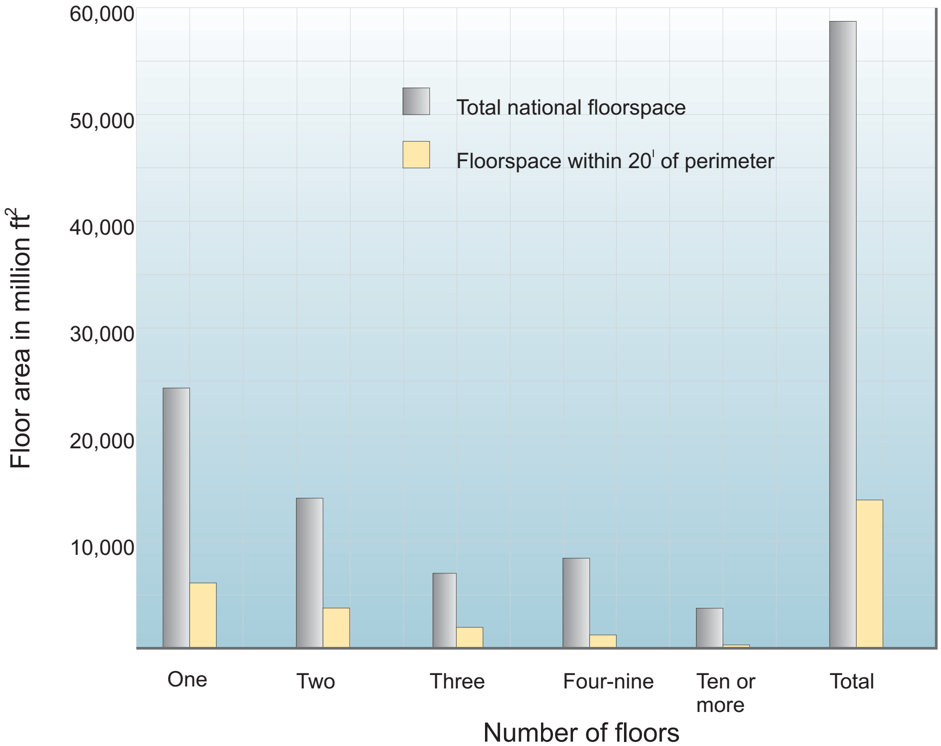

Figure 3-15 – Percentage of Commercial Floor Area Available for Daylighting by Sidelighting
Source: Heschong Mahone Group, based on CBEC's 1998 data, U.S. EIA

3.2.2 Resource Efficiency

Natural resources are extracted from the earth to manufacture lamps, ballasts, transformers, luminaires, lenses, controls and other lighting equipment. Energy and other resources are then used to manufacture the products. Additional resources and energy are used to package the products and to deliver them to distribution points and then to buildings. When their useful life is up, many lighting products end up in landfills. Some lighting products such as incandescent lamps last less than 1000 hours, so this process is frequently repeated for many products. Fueled by new construction and new lighting installations, the impact on natural resources and the environment is considerable.

Much can be done to reduce this impact, including: avoiding resource extraction from sensitive environmental areas, recycling materials and components, and using a high percent of recycled content for materials. Packaging can be made more efficient or reused. Some equipment manufacturers can ship products to job sites with only a minimum of packaging. And manufacturing and distribution can also be made more efficient.

A product's "embodied energy" is the total energy used to extract resources for that product, and then manufacture, package and distribute it. The amount of embodied energy in various building products is a growing concern among those interested in achieving "sustainable" architecture. A comprehensive analysis of embodied energy hasn't been published for lighting products.[1] However, in general, the energy consumed in operating a lighting product over its lifetime is likely to be far greater than is used to manufacture the product.

Products manufactured locally typically use less energy for shipping, and lighter and smaller products typically use less material and cost less to ship than heavier products. For example, the market shift from T-12 to T-8 and T-5 lamps has greatly reduced the amount of glass and rare-earth phosphors used per lamp and per lumen output. Shipping costs are also reduced due to their smaller size.

1 A search of international sources found no published data as of July 2000.

Products that can be shipped safely with less packaging, or with packaging that is easily recycled, should be preferred.

Similarly, any technique that extends product life also reduces energy and environmental impacts. For example, the use of photocontrols with a daylighting system might extend the life of lamps and ballasts by a factor of two, since they are used less often during the day. That means that embodied energy, mercury use and disposal costs are all reduced by half.

Comparing the resource efficiency or embodied energy of different manufacturing techniques is extremely tricky. These considerations are perhaps best addressed with clear incentives, economic or otherwise, directed toward manufacturers. The market would then be a primary force in working to reduce the impacts of each product.

3.2.3 Disposal Issues

Some lamps and ballasts contain materials that may be considered hazardous waste. Lead may be found in most incandescent and HID lamps while mercury is a component of all fluorescent and most HID lamps. Older ballasts may contain certain chemical compounds that are regulated as hazardous materials. Newer ballasts are specifically labeled when they are free of toxic chemicals. The lamp industry has been successful in dramatically reducing the mercury content of fluorescent lamps over the last few years and low mercury lamps are now readily available.

This section addresses the environmentally safe disposal of these lighting components.

Ballast Toxin Issues and Disposal

Modern electronic ballasts don't contain any hazardous materials requiring special disposal, but older ballasts may contain two chemical compounds: polychlorinated biphenyls (PCBs) and di(2-ethylhexyl)phthalate (DEHP). PCBs are found in fluorescent and high-intensity discharge (HID) ballasts manufactured through 1979 or lacking the label "No PCBs." DEHP has been found in ballasts designed for the following luminaires: 4-ft fluorescent luminaires manufactured between 1979 and 1985; 8-ft fluorescent luminaires manufactured between 1979 and 1991; and high-intensity discharge (HID) luminaires manufactured between 1979 and 1991. The proper method for disposing of used ballasts depends on several factors, such as the type and condition of the ballasts and the regulations or recommendations in effect in the states where you remove or discard them.

For information on the current requirements for ballast disposal, contact the environmental authorities for the state in which you wish to dispose of the products. Intact fluorescent and HID ballasts that are not leaking PCBs may generally be disposed of in a municipal solid waste landfill. The U.S. Environmental Protection Agency (EPA) has recommended packing and sealing the intact ballasts in 55-gallon drums and encouraged disposal of PCB-containing ballast wastes through high-temperature incineration, recycling, or a chemical or hazardous waste landfill. In addition, the federal Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), which regulates the disposal of hazardous waste, has required building owners and waste generators to notify the National Response Center when disposing of a pound or more of PCBs (roughly equivalent to 12 to 16 PCB-containing fluorescent ballasts) in a 24-hour period. Leaking PCB-containing ballasts have been required to be incinerated at an EPA-approved high-temperature incinerator. CERCLA has also required National Response Center notification for disposal of 100 pounds or more of DEHP in a 24-hour period (approximately 1600 DEHP-containing fluorescent lighting ballasts).

Lamp Toxin Issues and Disposal

Toxins found in lamps include lead and mercury. Lead may be found in most incandescent and HID lamps while mercury is an essential component of fluorescent and HID lamps. Fundamentally, fluorescent and HID lamps create light through the discharge of electricity through mercury vapor. Some lamps use more mercury for this purpose than others, and some lamp manufacturers have developed special low mercury products. In general, fluorescent T-8 lamps typically have less mercury than T-12 lamps. Compact fluorescent lamps generally have lower mercury than 4-ft fluorescent lamps. Eight-foot high output and very high output lamps generally have higher levels. Metal halide lamps are likely to have higher levels than high-pressure sodium lamps. Higher wattage lamps have higher levels of mercury.

Mercury-containing lamps may be considered hazardous waste, depending on their mercury content and the local regulating authority. The Toxicity Characteristic Leaching Procedure (TCLP) is a test used to determine how much soluble mercury or lead would leach into a landfill.

Federal laws in the United States have required building owners and waste generators to notify the National Response Center if they dispose of a pound or more of mercury (roughly equivalent to 10,000–20,000 4-ft T-12 fluorescent lamps!) in a 24-hour period. In addition to federal laws regulating lamp disposal, most states have their own laws dealing with mercury disposal. There are major variations state-by-state in lamp disposal requirements. The preferred method of disposal in most states is recycling. California has recently adopted the *Universal Waste Emergency Rules* that control the disposal of lamps with mercury content in large quantities. These rules are governed by the California Department of Toxic Substance Control and should be checked for their current status.[1] Contact information for each state, where current requirements can be obtained, is available at http://www.lamprecycle.org.

However, in balancing our concerns for reduction in toxins in our environment, it should be recognized that the largest manmade sources of mercury in the atmosphere has been fossil-fuel combustion. A coal-fired power plant may contribute about two to three times the amount of atmospheric mercury due to the energy use of an average fluorescent lamp when compared to the amount of mercury that might escape into the atmosphere directly from the lamp. On average, fossil-fueled power plants emit 0.04 milligrams of mercury per kilowatt-hour sold. Thus, maximizing the efficiency of lighting systems also minimizes mercury emissions from the power plants that provide electricity.[2]

Evaluation of Disposal Options

Any lighting upgrade project specification should include provisions for proper handling and safe disposal of lamps, ballasts and other hazardous materials that may be associated with the project. Under CERCLA, facility owners and operators and other people disposing of hazardous substances may be held liable for response costs, if there's a release or threat of a release of a hazardous substance into the environment. Disposal of mercury wastes or PCBs in an environmentally sound manner helps to minimize the potential for environmental contamination and liability. The overall impact of lamp disposal on the profitability of typical lighting upgrade projects is minimal. The disposal cost is significantly small compared to the cost of operating a lamp throughout its lifetime. Lamp disposal will generally extend the payback of a project by approximately one month.

Any measure that extends lamp life also reduces the net rate of mercury disposal. Thus, lamp products with better lumen maintenance and/or longer life can be replaced less often, as can lamps that are operated fewer hours per year due to the use of lighting controls. Both approaches reduce toxin impacts on the environment.

3.2.4 Light Trespass

Light trespass can be most simply defined as unwanted light from a neighboring property. It has become a subject of increasing concern as the prevalence and intensity of outdoor lighting has grown. Potential sources include street lighting, security lighting, sports lighting, billboards and signs, and car headlights. Indeed, any source of light can involve trespass if it impinges uninvited on neighboring property or public land. Such unwanted light can potentially be an annoyance, a serious nuisance or even a serious health and safety risk if it adversely affects visibility for other tasks.

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[1] Current status of California regulations governing lamp disposal can be found at http://www.dtsc.ca.gov.

[2] For additional information on lamp disposal, see: http://www.lightforum.com/design/wastedisposal.html.

Responding to these concerns, many local governments around the world have developed ordinances to control unwanted light. However, there has generally been little uniformity in approaches, definitions or enforcement methodology. Given that outdoor electric lighting is only about a century old and its exponential growth only a recent concern, there isn't an established body of law from which to draw in crafting these ordinances. In response, committees of the IESNA and the International Commission on Illumination (CIE) are currently meeting to refine definitions and develop a methodology to measure light trespass.

A Definition of Obtrusive Light

The International Commission on Illumination (CIE) defines obtrusive light as unwanted light that, because of quantitative, directional or spectral attributes in a given context, gives rise to annoyance, discomfort, distraction, or a reduction in the ability to see essential information. While the term "light trespass" implies unwanted light invading a specific piece of property, the more general international term "obtrusive light" does not address the issue of light crossing property lines.

Light trespass is generally divided into two different concerns—spill and glare. Spill is increased ambient illumination from a neighboring source, whether directly from the source or reflecting off of other surfaces. Glare is caused by an excessively bright source directly within view. Such sources of glare can be especially distracting, and thus annoying, as it is very difficult to avoid directing one's attention to a bright light source. Since people are typically looking toward the horizon, low angle sources of glare can be particularly troublesome, and most difficult to avoid visually. Sources of glare can also be temporarily disabling, preventing a person from seeing well under otherwise dark conditions. This is especially true for the elderly and visually impaired (See discussion on the aging eye in section 2.1.6, and discussion about glare in section 4.3.2.

As might be expected, sources of light trespass become more objectionable as they are more difficult to avoid visually, as they increase in size, increase in absolute brightness, are closer, and are in areas of lower ambient illumination (Lewin 1999). A reasonable metric of light trespass might be illumination at the eye of the viewer, perpendicular to the line of sight to the source.

Competitive Retail Lighting

Retail enterprises often compete with each other to have the brightest signs or the most brightly lit parking lot. This competition results in a constant ratcheting up of outdoor illumination levels, with each sign or building competing fiercely for the viewer's attention. Gas stations seem particularly susceptible to this rivalry, with some opposing street corners lit to 100 footcandles at night, even brighter than the interior of adjacent stores.

Safety

While the assumption may be that such high light levels contribute to a feeling of safety, so that people will be attracted to the gas station or store, the reality is quite different. The high light levels create a mis-adaptation of the eye at night. It takes significantly longer for the eye to adjust going from bright to dark, than dark to bright (see the discussion of illumination range in section 2.1.1). The eyes of the elderly are even slower to adapt. Thus, people leaving a very bright area have a much more difficult time seeing in the dark immediately afterwards, and are more susceptible to accidents. Bright light sources can also cause disabling glare for anyone outside of the area, reducing visibility and safety.

Because the elderly are especially susceptible to these effects of slow adaptation and disabling glare, many older people avoid driving at night, further reducing their mobility and independence.

Excess night lighting may also have negative health impacts. There is increasing evidence that exposure to light during the night may affect our overall health and immune response (see section **2.2** on Light and Health). In 1910, the average American slept nine hours per day. Now the average is close to seven hours per day (Coren 1996). Our round-the-clock lifestyles, supported by electric lighting, have seemingly resulted in an overall loss of sleep.

Recent Regulations and Initiatives

Just as some cities and town have noise ordinances, with different criteria by time of day, some towns may develop light trespass ordinances that vary by time of day, or may institute a lighting curfew. The CIE has proposed the use of "environmental zones" that define sensitivity to light trespass. The system proposes the use of four levels, E1 through E4, detailed in Table 3-3. Maximum illuminance levels for each zone and time of day can then be set. In order to be enforceable, measurement and enforcement procedures need to be defined.

Table 3-3 – Environmental Zones for Control of Light Trespass, proposed by CIE
Source: Lewis 2000.

Environmental Zone	Description
E1: Areas with intrinsically dark landscapes.	Examples are national parks, areas of outstanding natural beauty or residential areas where inhabitants have expressed a strong desire for strict limitation of light trespass.
E2: Areas of low ambient brightness.	These may be outer urban and rural residential areas. Roadways may be lighted to typical residential standards.
E3: Areas of medium ambient brightness.	This will generally be urban residential areas. Roadway lighting will normally be to traffic route standards.
E4: Areas of high ambient brightness.	Normally this category will include urban areas with a high level of nighttime commercial activity.

Other towns have chosen to define the type of equipment that can be used for outdoor lighting. These types of ordinances frequently specify full cutoff luminaires and limits on types of light sources. The International Dark-Sky Association maintains a catalog of current Outdoor Lighting Ordinances directed at limiting light trespass and/or light pollution (see http://www.darksky.org). The Electric Power Research Institute (EPRI) has also supported work analyzing potential recommendations and limits on outdoor lighting (Lewis 2000), and the National Electrical Manufacturers Association (NEMA) has developed a white paper on providing guidance on outdoor lighting code issues (NEMA 2000).

The U.S. Environmental Protection Agency has defined standards for Energy Star outdoor luminaires (primarily for residential applications) that include automatic controls, luminaire cutoff angles, and limits on lighting power—all designed to improve energy efficiency and reduce waste of outdoor lighting. IESNA has recently published an updated *Lighting for Exterior Environments* (RP-33-99) that discusses issues of light trespass, light pollution, and how to develop community outdoor lighting goals, guidelines, or ordinances.

For design guidelines to reduce light trespass and light pollution, see Advanced Guideline – Light Pollution and Light Trespass in section 4.3.1. Also see section 7.6 for a discussion of cutoff luminaires.

Possible Structure of an Outdoor Lighting Ordinance
(Derived from International Dark-Sky Association material.)

- Purpose of outdoor lighting
- The nature of light trespass
- Definitions
- Purpose of the ordinance
- Classification of outdoor areas
- Outdoor lighting requirements or limitations
- Curfew
- Exceptions
- Calculations or procedures
- Checking compliance, or enforcement methodology

3.2.5 Light Pollution

Many modern city dwellers have never seen a prime dark sky, as urban sky glow has removed the view of the universe that people had only a generation or two ago. Outdoor lighting has only been with us for one century; for all previous centuries a view of the dark sky in its full glory was a nightly experience. Some national parks in the United States are now considering limiting their nighttime lighting in order to preserve the view of stars as part of our natural heritage (Doyle 1999). This is an important but minuscule step. But should we have to travel to a national park in order to show our children the stars? Where will they be able to experience infinity?

Figure 3-16 – Night Sky in Tucson
Source: International Dark-Sky Association

The urban sky glow at some observatories is now at such a high level that closures are being considered. Mt. Palomar Observatory, whose primary telescope still houses the largest monolithic mirror in the United States, suffers from a sky glow level twice that of the natural background. This has reduced its sensitivity to 40% of its original level. Mt. Wilson in Los Angeles has been reduced to about 11% of its original sensitivity by an average sky glow five times greater than normal (IDA 1996). Astronomers have taken action to limit light pollution in communities near to observatories. This campaign has perhaps been most successful in Tucson, Arizona, a city with a well-established outdoor lighting ordinance.

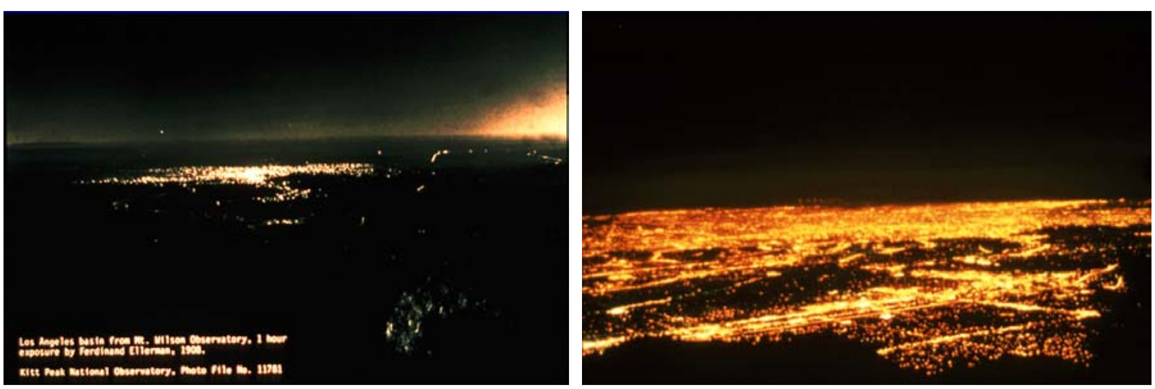

Figure 3-17 – Views of Los Angeles from Mt. Wilson
1908 (left) and 1988 (right) Source: International Dark-Sky Association

In a prime black sky, low clouds appear black against the sky. In a sky with urban sky glow, clouds appear white, or even yellow, pink or green depending on the primary source of the street lighting.

Sky magnitude is a scale between 1 and 7 that describes the relative visibility of stars or the darkness of the sky. The faintest stars visible to the naked eye can only be seen at sky magnitude 7, which is also referred to as a prime dark sky. It is possible to see as many as 14,000 stars at sky magnitude 7, although under ideal conditions any given observer should be able to see somewhat less than half of them, or about 7000. Only about a third of this population of stars can be seen at sky magnitude 6.

With each increase in light pollution (reduction in sky magnitude), fewer and fewer stars are visible, until only the very brightest stars can be seen over the skies of our largest cities. The relationship between light pollution and the number of stars visible is summarized in Table 3-4.

Table 3-4 – Light Pollution Effects on Visible Stars
For comparison, a candle flame observed at a distance of one mile away is about as bright as a magnitude 2 star in the sky.

Pollution Degree	Sky Magnitude	Visible Stars	Example Location
Prime dark sky, clouds black	7	7000	100 miles from nearest city
2/3 of stars no longer visible, clouds visible	6	2400	Remote rural areas
Milky Way barely visible	5	800	Outer edges of cities
Serious light pollution	4	250	Typical suburbia
Severe light pollution	3	50	Downtown of major cities
Severe light pollution	2	25	Downtown of largest cities

Evidence from satellite photographs clearly shows the burgeoning nature of nighttime lighting all over the world. Cities can be easily identified at night, and some urban corridors show continuous streams of light hundreds of miles long. From the photos in Figure 3-18, it's clear that some city dwellers may have to travel very far to view a prime night sky.

Sky glow has two components, direct light going up into the atmosphere and reflected light off the ground or other surfaces. Direct light can be controlled by the type of luminaire selected and its installation. Refer to section 7.6 for information on exterior luminaires and their light distribution properties. Reflected light is controlled by not overlighting exterior areas such as gas stations, car dealerships and parking lots. Refer to section 5.9 for information on gas station lighting. Also, controlling exterior lighting such that nonessential lighting is turned off in the late evening or lighting is controlled by motion sensors, will lessen the sky glow potential for professional and amateur astronomers. Refer to section 8.3 for information on motion sensors.

Near horizontal light is actually the most problematic source of light pollution for astronomers because it intersects the largest amount of air mass on its exit through the atmosphere. A light ray aimed straight up escapes quickly, whereas a ray aimed at 10 degrees above the horizon travels through 5.6 times as much atmosphere—"polluting" it all the way. Thus, the use of cutoff luminaires that reduce this scattering of light from low angle sources can make a very important contribution to the reduction of light pollution.

Figure 3-18 – Wasted Light Escaping to Space
Composite images created from satellite photos
Source: International Dark-Sky Association

Impacts on the Biosphere

Excessive light can have an adverse effect on livestock and wildlife. For example, chicken farmers have learned that 24-hour lighting disturbs the growth of chicks. It is well known that night lighting disturbs the behavior of nocturnal insects. Some entomologists have blamed the increase in night lighting on declines in certain moth populations (Frank 1988). While a direct causal mechanism has not been proven, there is a related concern that a decline in moth populations will have an impact on the populations of the wildflowers that the moths pollinate. Baby sea turtles are instinctively attracted to bright lights. Thus the cities in Delray Beach, Florida and Isle of Palms, South Carolina have passed ordinances limiting light along beaches to avoid attracting nesting mothers and hatchling turtles toward the city and sure death on the highways. Others have noted that bright lights at night, especially from shrimp boats at sea, seem to interfere with the migration of birds. Thus light pollution can potentially have long-term effects on the animal and plant life of this planet.

Impacts on Energy Use

The total amount of energy used for outdoor lighting isn't well understood. Recent studies quantifying lighting energy use have generally excluded outdoor lighting from their purview. While street lighting is generally estimated to constitute about 1% of total lighting energy use, the amount of energy use for outdoor lighting for homes, commercial and industrial buildings is essentially unknown (Heschong Mahone Group 1997).

Any light that is not used for its intended purpose—to make things more visible—is wasted, and hence is unnecessary. The amount of energy wasted in outdoor lighting at night is truly astronomical. The light lost to space has already escaped the atmosphere. A much greater percentage of night lighting is lost to inefficiencies closer to home. Overlighting and inefficient systems lose light internally, then unnecessarily lose additional light when it is absorbed by the leaves of trees and by dark surfaces, or spilled onto neighbor's property.

Recent Regulations and Initiatives

In addition to the outdoor lighting ordinances discussed in Light Trespass above, other legal approaches can reduce light pollution and help to reduce the motivations that are driving our communities to ever increasing outdoor light levels.

Many commercial building owners install high lighting levels around their properties because they are worried about the threat of a lawsuit from someone claiming that the lighting conditions contributed to an accident—whether a sprained ankle or a bashed car. Establishing community standards for outdoor lighting can provide an effective counter to this argument, since the standard would represent local consensus on what is acceptable practice. The illumination level available from a full moon has been suggested as one reasonable nighttime lighting level of illumination since this is the maximum that nature provides. Another legal approach is for a community to pass a "hold harmless" clause stating that a property owner cannot be held responsible for events that occur due to natural darkness. This returns the presumption of the law to lighting conditions available in the natural world, without the addition of electric lighting.

3.3 Lighting Policies, Codes and Standards

Since lighting systems account for so much energy use, the efficiency of lighting is the focus of many policies, codes and standards at the national, state and local levels. These can be broken down into five basic categories:

- **Energy policies and standards** seek to encourage the use of efficient equipment through governmental or corporate procedures, such as purchasing preferences and regulations, education programs, technical assistance, project funding and research.
- **Utility programs** seek to encourage the use of efficient lighting through various marketing efforts, educational outreach, technical assistance, rebates on equipment, incentives to owners, and/or purchasing programs with manufacturers.
- **Appliance standards** regulate the efficiency, and other performance characteristics, of particular products, such as lamps or ballasts, that may be manufactured or sold on the market.

- **Building energy codes** set a minimum level of efficiency for lighting systems in buildings, prescribe and/or encourage control strategies, and establish methodologies for demonstrating compliance.
- **Labeling programs** seek to identify the most efficient products and/or buildings in order to facilitate growth in consumer demand for those products. Such programs include both government-led initiatives, such as EPA's Energy Star, and private initiatives, such as LEED (Leadership in Energy and Environmental Design).

In addition to these energy efficiency-related initiatives, the lighting industry is affected by many other codes, regulations and standards. These include:

- **Construction codes,** which set standards of construction and safety for electrical and lighting systems. The Americans with Disabilities Act, or ADA, sets standards for meeting the safety needs of building occupants.
- **Disposal regulations,** which determine the labeling, handling and disposal of products that contain hazardous materials.
- **Industry standards,** such as American National Standards Institute (ANSI) and Underwriters Laboratories (UL), which set requirements for product performance, interchangeability and safety.
- **Recommended practices,** such as those issued by IESNA, which describe currently accepted good practice in design and in the field.

This complex of policies, standards, regulations and recommendations creates the context within which the lighting industry functions and influences how lighting systems ultimately are implemented in buildings. It is beyond the scope of the *Advanced Lighting Guidelines* to detail all of these elements. Rather, these Guidelines attempt to highlight the key components for advanced lighting design, and refer the reader to the many excellent sources for detailed and current information on their status.

3.3.1 National Energy Policy and Standards

A number of national initiatives in the United States continue to promote lighting efficiency in both the federal sector and the private sector.

The federal Energy Policy Act of 1992 (EPAct) had a major impact on lighting in commercial buildings. It outlawed the manufacture of a number of inefficient or high wattage lamp types, most especially the cool white 40 W fluorescent lamp, which had been a standard in most commercial buildings. It required the labeling of luminaires for energy efficiency, set goals for the federal government, and encouraged states to adopt energy codes.

The federal government has helped support the development of national energy standards such as ASHRAE/IESNA. To set a good example, it also adopted an energy code for federal buildings, Title 10 (10 CFR 435), based on the ASHRAE/IESNA standard. In 2001, a revised version of Title 10, called FEDCOM I (10CFR 434), will take effect. In addition, a number of executive orders, such as Executive Order 12902, have mandated federal government energy-savings goals and enabled the creation of many programs to support those goals.[1] Reduced energy use for lighting has been one of the prime targets of all these programs.

In addition to model building codes, the federal government also issues minimum energy efficiency standards that are mandatory for product manufacturers. A recent example of this is the ballast efficiency standards, developed with industry consensus, which will effectively require T-8 lamps and electronic ballasts for all standard commercial applications by 2005.

The Federal Energy Management Program (FEMP) of the U.S. Department of Energy has been the primary agency charged with promoting greater energy efficiency within the federal government. This

[1] The text of EPAct and the Executive Orders can be ordered from http://www.eren.doe.gov/femp.

office has developed a set of analysis tools, training programs, technical assistance resources and case studies that are available through their Web site.[1]

Under the direction of FEMP, the Buying Energy Efficient Products Program provides guidance to help federal buyers purchase energy efficient products. FEMP issues a series of Product Energy Efficiency Recommendations in the Buying Energy Efficient Products binder, that identify the upper 25th percent of efficiency for over 36 energy-using products, including various light sources, exit signs and luminaires. Presidential Executive Order 13123 (June 3, 1999), in conjunction with the Energy Policy Act of 1992 (EPAct), establishes a clear mandate for "...federal agencies to purchase energy efficient products, including all ENERGY STAR labeled products or, for product groups where ENERGY STAR programs do not yet exist, products that are in the upper 25th percent of energy efficiency as designated by FEMP." Further supporting this federal energy efficient purchasing policy is the Federal Acquisition Regulations (FAR 48 CFR 23.704), which mandates that "agencies shall implement cost-effective contracting preference programs favoring the acquisition of ... products that are in the upper 25th percent of energy efficiency for all similar products."[2]

In addition, during 1999 and 2000, the U.S. Department of Energy worked with a wide range of lighting industry participants to develop a "roadmap" for future investments in research and development of lighting technology. A simple vision statement (see the sidebar The Lighting Vision 2020) was developed by consensus process to guide this work, which reads like a good definition of "advanced lighting" as discussed in these *Advanced Lighting Guidelines*.

The Lighting Vision 2020

In 2020, lighting systems in buildings and other applications will:

- Enhance the performance and well being of people,
- Adapt easily to the changing needs of any user,
- Use all sources of light efficiently and effectively,
- Function as true systems, rather than collections of independent components; fully integrated with other systems,
- Create minimal impacts on the environment during its manufacturing, installation, maintenance, operation, and disposal.

As a result, people will understand, value, and utilize the tangible, personal benefits provided by these lighting systems.

Energy Star

The U.S. Environmental Protection Agency, in collaboration with the U.S. Department of Energy, has incorporated a number of lighting efficiency elements into its "Energy Star" program. Energy Star is fundamentally a marketing program, aimed at helping consumers to identify energy efficient products and systems and at encouraging manufacturers to produce more energy efficient products. It also sets minimum standards of performance for products to earn the Energy Star label. Most of these, such as Energy Star lamps and Energy Star luminaires, are aimed more at the residential market, but have some relevance to small commercial applications.

The Energy Star Buildings program, along with its GreenLights counterpart, encourages lighting system energy efficiency in commercial buildings through technical information and support. All Energy Star programs are structured as partnerships between manufacturers, service providers, and the government. They are voluntary, market-driven programs, rather than mandatory regulatory programs, and the Energy Star brand has done much to promote energy efficiency in the marketplace.

[1] For more information, go to http://www.eren.doe.gov/femp.

[2] The EO and FAR documents can be downloaded at http://www.eren.doe.gov/femp/procurement/challenge.html.

The LEED Green Building Rating System

The LEED Green Building Rating System is a voluntary rating system for new and existing commercial, institutional, and high-rise residential buildings. Developed by the U.S. Green Building Council, a voluntary organization representing a wide range of the building industry, the rating system evaluates environmental performance from a "whole building" perspective over a building's life cycle, providing a standard for what constitutes a "green building." LEED is based on accepted energy and environmental principles and attempts to strike a balance between known effective practices and emerging concepts.

Energy-efficient lighting contributes to credits available in the rating system's Energy and Atmosphere section by reducing the building's simulated energy performance as compared to a base case building meeting ASHRAE/IESNA Standard 90.1-1999. Daylighting schemes that provide views and connection with the outdoor environment earn additional credits in the Indoor Environmental Quality section. For more information about LEED, visit the U.S. Green Building Council Web site at http://www.usgbc.org.

3.3.2 Energy Codes

Energy codes establish a minimum level of energy efficiency or product performance for lighting systems installed in buildings. However, energy codes also have a number of more subtle functions in raising the overall energy efficiency and level of design practice for lighting systems, and buildings in general, such as:

- *Lighting System Energy Efficiency:* For lighting systems, the basic energy efficiency requirement of energy codes is to restrict the lighting power, or total installed wattage, of the system. The lighting power limit may be specified at the whole building level, by space categories, or by individual tasks. These requirements are performance specifications, not detailed instructions on how to design lighting systems. In addition to lighting power limits, energy codes typically call out lighting switching and automatic control requirements, which are intended to assure that lighting systems can be efficiently operated. It remains the responsibility of the lighting system designer to provide all the other requirements of good lighting—adequate task illumination, good contrast, lack of glare, functional controls, etc.—while keeping within the lighting power limits set by the code. One of the purposes of this document is to provide lighting designers with the information they need to meet energy code requirements and yet design good lighting for building occupants.
- *Code Compliance and Enforcement:* Energy code compliance activities help to improve the energy performance of new buildings by establishing reasonable standards of energy efficient design practice. Code enforcement gradually eliminates the extremes of bad practice and reduces the number of buildings falling below the current energy code. Together, compliance and enforcement activities establish a minimum standard of practice that building owners can expect to find in the buildings they purchase or construct.
- *Education Incentives:* Energy codes create an incentive for practitioners to learn more about lighting efficiency, in order to have an easier time meeting the code, and to design better lighting within the code constraints. The presence of energy codes has been one of the main motivators for practitioners to attend lighting training courses and pursue information about new, more efficient technologies. An energy code may be the reason that you are currently reading this document.
- *Manufacturing Incentives:* Energy codes can create a competitive advantage for more efficient products that can meet the code more easily. Energy codes that are technology-neutral are more likely to spur innovation. Codes that favor the use of one type of product are likely to result in an industry that becomes highly vested in the continuance of those code provisions.
- *Program Baseline:* Energy codes provide a baseline against which voluntary or market-driven utility and government programs can establish incentive programs. The code requirements also provide a baseline against which program progress can be measured over time.

- *Code Revision:* Energy code revisions gradually increase the efficiency standards that all buildings must meet. Thus, as overall practice improves, the code baseline can be moved toward greater efficiency.

State and National Energy Codes

There is a wide variety of energy codes and standards. These range from national model energy codes, which must be adopted by a state or local jurisdiction to have the force of law, to locally developed and adopted standards.

EPAct (discussed above) has also had the effect of bringing mandatory lighting efficiency standards to many states that previously had none. There are three national model energy codes that are widely used by states and local jurisdictions. ASHRAE/IESNA Standard 90.1–1999, and its older edition Standard 90.1–1989, were developed by the two major professional societies concerned with lighting energy efficiency. These standards have been adapted and adopted by a large number of states and local jurisdictions across the country, with some local amendments and refinements added along the way. The third major national model energy code, the International Energy Conservation Code or IECC, adopts the ASHRAE/IESNA Standard 90.1 by reference, plus it provides a simplified compliance path with equivalent energy efficiency.

A transition is currently underway among the jurisdictions that have adopted energy codes based on Standard 90.1, from the older and outdated 90.1–1989 to the updated 90.1–1999. In developing the 1999 standard, ASHRAE/IESNA based the lighting efficiency requirements on current standard lighting technologies, such as T-8 fluorescent lamps with electronic ballasts. This resulted in significant reductions in lighting power allowances compared to the older 90.1–1989 standard, which was based on T-12 lamps and magnetic ballasts. Similar improvements in lighting efficiency were applied to the other types of available lighting equipment.

In adopting local ordinances to establish energy codes, jurisdictions often develop local amendments. For example, the state of Colorado adopted the 90.1–1989 standard, but adjusted the lighting control requirements, and added a minimum luminous efficacy requirement that effectively rules out widespread use of the old T-12 magnetic-ballast fluorescent luminaires.

In addition to energy codes based on the 90.1 family of model standards, a number of states have developed their own lighting efficiency standards. Because of its large population and construction volumes, California's Title 24 Energy Efficiency Standards for Residential and Nonresidential Buildings have produced very substantial energy savings over the years, and have lead to relatively high standards of energy efficient lighting design compared to many other regions of the U.S. Other states, such as Washington, Oregon, Minnesota and New York, have also developed their own energy codes; in some cases starting from scratch and in other cases creating local variations of energy codes developed elsewhere. It is too large a subject to attempt a detailed comparison of all these codes, but they tend to have several characteristics in common.

The following tables compare the lighting efficiency requirements of the 90.1–1999 standard to the 1995 and 1998 California standards. The comparisons are in terms of allowed lighting power density in W/ft². The allowed lighting power can be determined for the whole building (Table 3-5) or on a space-by-space basis (Table 3-6). The space types in Table 3-6 are an example for just one building type, schools.

Table 3-5 – Comparison of Whole Building Lighting Power Allowances (W/ft²)
Source: Eley Associates, An Analysis of ASHRAE/IESNA Standard 90.1–1999 and California Title 24–1998, prepared for Pacific Gas and Electric (PG&E), July 2000

Standard	Office	Retail	Assembly	School
California 1995 (whole building method)	1.50	2.00	2.00	1.80
California 2001 (whole building method)	1.20 (Note 1)	1.70	1.80	1.40
ASHRAE 1999 (building area method)	1.30	1.90	1.60	1.50

Note 1: The 2001 California standard makes it clear that the office lighting power allowance includes task lighting. In open offices greater than 250 ft², the standard requires that 0.2 W/ft² be assumed for task lighting, even if no task lighting is shown on the plans and specifications.

Table 3-6 – Space-by-space LPD Comparison: ASHRAE/IESNA Std 90.1–1999 & CA 2001
These comparisons are made in the context of a school and are intended for comparative purposes only. Source: Eley Associates, An Analysis of ASHRAE/IESNA Standard 90.1–1999 and California Title 24–1998, prepared for Pacific Gas & Electric (PG&E), July 2000

Space Type	California 2001 Building Area Method	ASHRAE 1999 Space-by-Space Method
Enclosed Admin/Office	1.3	1.5
Open Admin/Office	1.3 (Note 1)	1.3
Art	1.6	1.6
Class Room	1.6	1.6
Commons Cafeteria/Dining Area	1.1	1.4
Corridor	0.6	0.7
Library – Reading	1.2	1.5
Library – Stacks	1.5	1.9
Kitchen	1.7	2.2
Theatre Auditorium	1.4	1.8
Band and Choir Spaces	1.6	1.6
Gym – Play	1.0	1.9
Gym – Exercise	1.0	1.1
Shower Room	0.8	0.8
Science Lab	1.6	1.6
Teacher Resource (Prep)	1.3	1.5
Team Resource (meeting)	1.3	1.5
Technology, Shop	1.5	1.5
Toilets	0.6	1.0
Support / Utility	0.6	1.3

Note 1: The 2001 California standard makes it clear that the office lighting power allowance includes task lighting. In open offices greater than 250 ft², the standard requires that 0.2 W/ft² be assumed for task lighting, even if no task lighting is shown on the plans and specifications.

ASHRAE/IESNA 1999 and California both have building area and space by space methods for determining lighting power densities. Some places like Oregon have greatly simplified the lighting requirements to match Uniform Building Code (UBC) classifications and some states such as California have a third, more detailed procedure for determining lighting power that is directly related to IESNA illumination categories. California and ASHRAE/IESNA 1989 have credits for automatic lighting controls but ASHRAE/IESNA 1999 does not. ASHRAE/IESNA 1989 has an complicated systems of control points while the control requirements for ASHRAE/IESNA 1999 and California are more prescriptive.

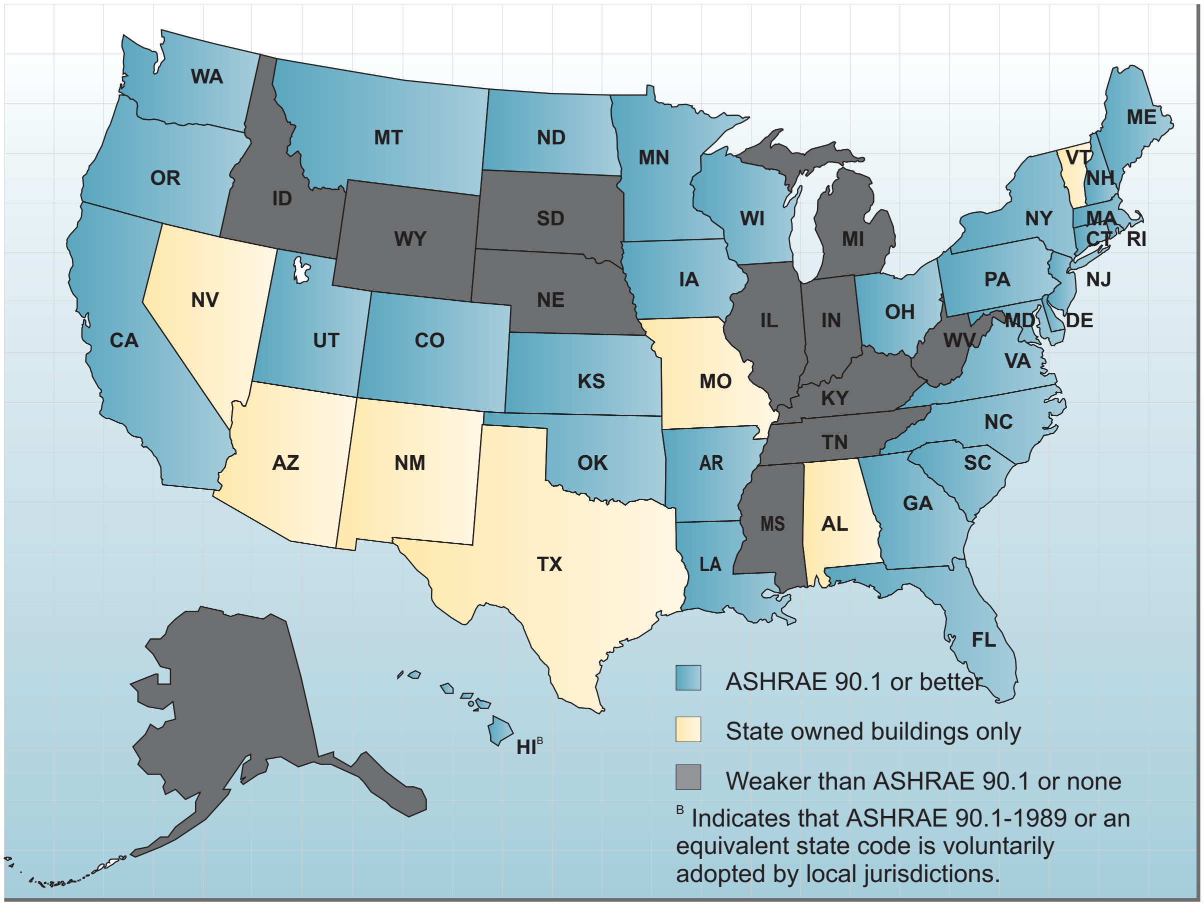

Figure 3-19 – State Adoption of EPAct-compliant Commercial Energy Code

This data is current as of Summer 2000. Source: http://www.bcap-energy.org. Note: The ASHRAE 90.1 or better label is in reference to the 1989 version of the standard. ASHRAE and IESNA adopted a major update in 1999 and comparisons against this later standard are not available.

Energy Code Structure

Energy code requirements for lighting may be grouped into several broad categories.

- *Lighting Power Limits.* Lighting power limits establish a maximum allowable installed lighting power level. The limits are typically expressed in watts per square foot (W/ft^2); the value is multiplied by the area of the space to determine the limit. These may be given as whole building limits, with a single W/ft^2 limit that applies to all the spaces in a building. They may also be given by space category, with higher values for spaces with more demanding visual tasks.

For buildings with special lighting needs, the whole building or space category method may be too low to serve the building's needs. In these cases, energy codes may provide special lighting power allowances. Some codes also provide extra lighting power allowances for special applications on a "use it or lose it" basis. These allowances only apply to the specific lighting equipment used to illuminate the special application; they may not be used as general allowances to boost the whole building lighting power limit.

Most energy codes also provide a whole building performance-based method for setting an overall building energy budget, allowing users to obtain higher lighting power allowances by trading off lighting energy with other building components.

- *Outdoor Lighting Power Limits.* A few codes also address buildings' outdoor lighting, such as lighting of facades, canopies, walkways and parking. These requirements seldom address outdoor lighting that isn't powered from the building's electrical system, such as roadway lighting.

- *Calculation of Installed Lighting Power.* Energy codes that specify limits on installed lighting power also include rules for calculating the installed lighting watts. These rules require identification of the types and quantities of lamps, ballasts and luminaires, and the wattage of lamp/ballast combinations. Default lamp/ballast wattages may be used when the equipment's make and model is unknown. These rules encourage designers to select more efficient lamp/ballast/luminaire combinations, because they yield lower installed wattages, but they also require designers to document the equipment's better performance.
- *Mandatory Switching Requirements.* Most energy codes include mandatory requirements for lighting controls that must be applied to all building designs (with some exceptions) and are typically independent of the lighting power limits. Mandatory controls requirements may call for independent light switches in every room, bilevel switching or daylit area switching, photocell controls on outdoor lighting, etc. Many of the updated energy codes include a requirement for automatic sweep controls that shut off building lighting during typically unoccupied hours.
- *Mandatory Control Specifications.* Energy codes also typically set minimum performance requirements for automatic lighting controls, to assure that they are likely to function as intended and not cause user dissatisfaction. These requirements may include time delays for occupancy sensors, or sensitivity adjustments for photocell controls.
- *Optional Lighting Control Credits.* Some energy codes also provide credits for automatic lighting controls that are installed as options, allowing the designer to calculate a reduced, adjusted lighting power level, in exchange for installing automatic controls. If the adjusted lighting power meets the code's allowable maximum, then the design complies. In effect, the designer trades off the energy savings expected from the automatic control for the extra energy use from the increased lighting power. Controls credits can provide greater flexibility in meeting lighting power limits, and they encourage the use of automatic controls that can produce a net savings in lighting energy over time. Lighting control credits have been offered for such devices as occupancy sensors, daylighting photocontrols, tuning controls, and lumen maintenance controls.
- *Compliance Documentation.* More advanced energy codes typically provide standard forms for demonstrating a lighting design's compliance with requirements. Some jurisdictions also provide compliance software tools to prepare documentation electronically. Codes may also require the plans show a certain level of specificity of lighting system elements and controls. These requirements can make code enforcement more successful, leading to greater energy savings.

California Lighting Compliance

Figure 3-20 shows the distribution of energy efficiency among a sample of 667 new buildings, representing the four major commercial building types, built in California from 1994–1998. The energy ratio compares the as-built energy efficiency of a given building to the energy efficiency specified by the 1995 Title 24 building energy efficiency standards. An energy ratio of 1.0 indicates a building that just meets the energy code. Buildings with energy ratios lower than 1.0 use less energy (are more efficient) than the code requires. Buildings with energy ratios greater than 1.0 do not meet code. These indicate a need for more effective code enforcement.

Overall, these data show that the large majority of buildings were more energy efficient than the version of Title 24 that they were required to meet. This suggests that at this point standard practice has probably advanced sufficiently such that the energy code requirements could now be made more stringent, to reflect current good practice, and thereby encourage a higher standard of energy efficiency for all buildings. Indeed, in 1998 and again in 2001, the California standards were updated to incorporate some of this change in standard good practice.

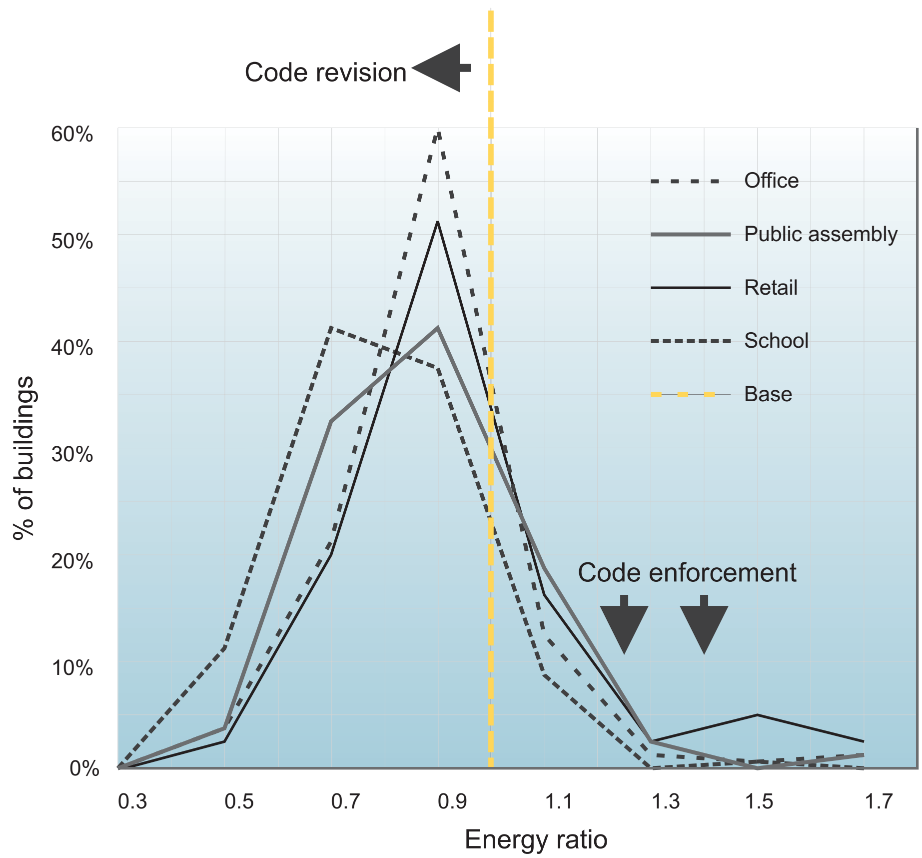

Figure 3-20 – The Dual Role of Codes: Whole Building Energy Use Relative to Code Standards
Source: RLW Analytics, Nonresidential New Construction Baseline Study, July 1999

The arrows in Figure 3-20 indicate areas where policy efforts will have an affect. Policymakers often must decide where to invest limited resources. More stringent code enforcement will reduce the number of buildings that exceed the energy use mandated by the code, i.e. those with an energy ration greater than 1.0. Code revisions that increase stringency are likely to cause the majority of buildings at the peak of the curve to shift to higher efficiencies. While code enforcement should be an essential component of any code program, in this particular case this graph shows that more energy is likely to be saved by increasing code stringency compared to more stringent enforcement, since a much larger population of buildings would be affected.

This same study found that most commercial buildings have lighting systems that were better (had lower installed lighting power) than code requirements, and concluded that three-fourths of all recent energy savings in commercial building could be attributed to lighting efficiency measures (RLW Analytics 1999, 132). Of course, such a calculation is a function of comparing current building designs to a baseline of code requirements. As code requirements increase in stringency, as they did with the 1998 Title 24 standards, this relative margin of savings is decreased.

While utility programs have been effective in encouraging higher levels of lighting efficiency, the study shows that at this point most buildings that did not participate in a utility program are also substantially more efficient than code.

Table 3-7 – New Construction Lighting Energy Use for 4 CA Bldg. Types (1994–98)
Source: RLW Analytics, Nonresidential New Construction Baseline Study, July 1999

Building Type	**Average LPD W/ft²**	**Lighting Average kWh/ft²**	**% Sites Better than Code**	**Net Energy Use vs. Code**
Office	1.22	4.0	85%	88%
Public Assembly	1.27	3.5	77%	88%
Retail	1.64	8.2	75%	89%
Schools	1.37	3.2	91%	79%

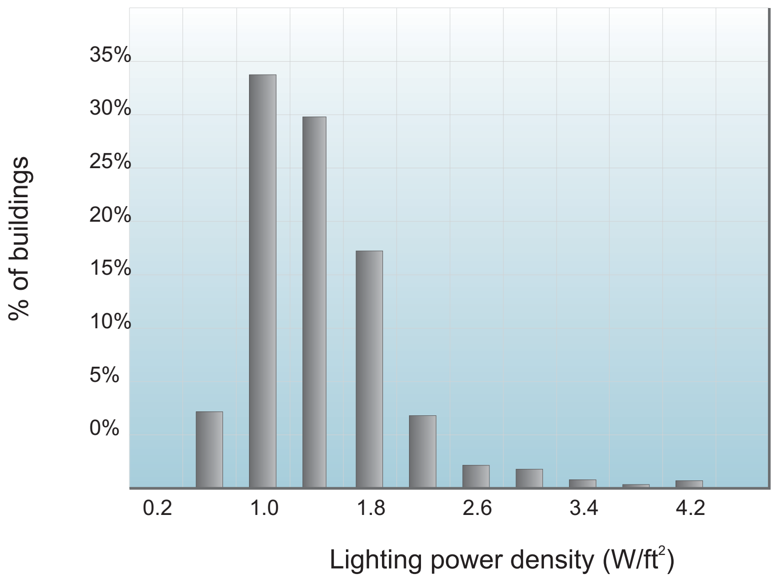

Figure 3-21 – Distribution of Overall Lighting Power Density (W/ft²)
Lighting power density distribution for offices, schools, retail and public assembly spaces constructed in California between 1994–1998. Source: RLW Analytics, Nonresidential New Construction Baseline Study, July 1999

Figure 3-21 makes it clear that there is a wide distribution of levels of lighting energy use across commercial buildings. There may be many reasons for this range of values. Some building types are allowed more lighting power, some may not be complying with the code, some may have special conditions that allow a higher lighting power density, and some portion of the spread may be attributable to measurement error.

The data presented here illustrate some of the characteristics of the California population of commercial buildings, and suggest some conclusions about the role of energy codes in encouraging lighting system efficiency. Energy codes, of course, are concerned with large populations of buildings. The lighting designer, by contrast, is concerned with matching the building occupants' requirements to the owner's budget and to the constraints of the building code. The data show that for most buildings in California, this is being done, and suggest that for all buildings it is possible. The information presented throughout the *Advanced Lighting Guidelines* can assist the lighting designer in choosing technologies and equipment to most effectively design an energy efficient lighting system.

Standard Input Values

Most organizations now realize that a standardized format for computer data is an enormous benefit to all. The National Electrical Manufacturers Association (NEMA) and IESNA have taken a lead in standardizing the format of specification and performance data for various lighting products. A similar effort is underway in the world of energy codes and energy analysis to standardize inputs for energy analysis of lighting installations. The 1993 edition of the *Advanced Lighting Guidelines* helped initiate this process by publishing standard wattage and lumens per watt values that could be used as defaults (Table 3-17 of the 1993 edition). As compliance with energy codes becomes more computer oriented through the use of aids such as ComCheck E-Z, the use of standardized defaults becomes essential.

A related effort is underway to make building design and analysis software talk to each other. The International Alliance for Interoperability (IAI) is developing a standard data model for software interoperability for buildings, referred to as the Industry Foundation Classes (IFC). The major building computer-aided design (CAD) vendors are making their software interoperable using the IFC. To date, this work has been limited to geometry, but energy features of buildings are likely to be addressed soon. This effort promises an ability to link data collection and analysis for building audit software, labeling program certification, and energy simulation and code compliance software.

3.3.3 Construction Codes

Electrical Construction Code (NEC and local)

Before there were energy efficiency codes, there were electrical codes to regulate the safety of lighting systems and to prevent hazards such as fire or shock. The primary U.S. national model code for electrical systems is the National Electrical Code (NEC). There are numerous local variations of electrical codes (for example, San Francisco, New York City, Los Angeles), and some jurisdictions adopt the NEC with local amendments. The full variability of these codes cannot be described here, but the most common NEC requirements affecting lighting systems can be summarized as follows:

- Article 410 generally covers and restricts typical lighting. It is closely related to Underwriters Laboratories (UL) listing standards for the intended application. While most of the code's requirements are covered in UL listings and have a minimum impact on application, there are a few very important aspects of this article that dramatically affect everyday practice, including where lights can be placed in a closet, requirements for thermally protected and insulated ceiling lights, and other requirements. The section on track lighting was changed in 1996 to permit essentially unlimited track length on a branch circuit, making track newly viable in retail and gallery display lighting.
- Article 411 was created in 1996 to deal with the rapidly evolving low voltage lighting systems market.
- Articles 500–699 deal with specific requirements for unique space types. For instance, article 680 restricts lighting above and around pools, fountains, spas, etc.
- Article 725 deals with the unique power supply requirements for low voltage lighting.

Safety and Access Codes (NFPA101, ADA)

In addition to the electrical code, fire codes and codes dealing with accessibility for disabled persons have provisions governing some aspects of lighting.

In the United States, the National Fire Protection Association code, NFPA101, the Uniform Building Code (UBC), and other building codes typically state requirements for normal and emergency egress illumination, usually in footcandles, to assure that there will be adequate illumination for vacating a building under fire or other emergency conditions. Emergency lighting must be on a special battery or non-interruptible source.

The U.S. federal Americans with Disabilities Act (ADA), and the code requirements that derive from it, mostly affects luminaire projection into the path of egress, so as not to impede egress by disabled persons. There may be other implications in the future.

Listings

For the most part, the various code requirements described above apply to equipment designers and installers. In addition, there are listing requirements for electrical equipment that must be met by the manufacturers. Lighting designers merely need to specify listed equipment; it's up to the manufacturers to make products that meet the requirements, and to submit them to testing laboratories to ascertain that they meet requirements. These requirements include such details as grounding, prevention of shock, operation under damp or wet conditions, resistance to flame, etc. The standards of UL are used for testing and listing products for use in the United States. Any accredited lab can test and list products; the two most common labs are Underwriters Laboratories (UL) and ETL. In Canada CSA International and in Mexico NOM (Normas Oficiales Mexicanas) provide similar functions. Listed products earn a label, which must appear on the product in order to comply with electrical codes that require the use of listed products.

3.3.4 Standards of Practice

National Council on Qualifications for the Lighting Professions (NCQLP)

Lighting practitioners come from a wide variety of educational backgrounds, such as electrical engineering, architecture, and theater design, to name just a few. Because of this diversity in backgrounds, there had been no single educational or professional organization that could certify the expertise of lighting practitioners as is commonly done by other building design professions.

Recognizing the importance that lighting design has on the safety, energy efficiency and functionality on the built environment, many lighting industry and governmental organizations joined together to help establish the National Council on Qualifications for the Lighting Professions (NCQLP). Founded in 1991, NCQLP has established a certification program for the lighting industry. Lighting practitioners who can prove they have sufficient education or experience, and who successfully pass a certification exam, are granted "Lighting Certified" status by NCQLP and can use the appellation LC after their name. LC status indicates that a person has met or exceeded standards that demonstrate lighting expertise.[1] Building owners can now specify that any lighting practitioner who proposes projects for their buildings must first be "Lighting Certified" as an assurance of knowledge and professionalism.

International Association of Lighting Designers

The International Association of Lighting Designers (IALD) is an organization of independent lighting designers whose mission is to serve worldwide members by promoting the practice of excellent lighting design. To further this goal, IALD participates in relevant research and standards setting, and actively recognizes practitioners that have contributed to superior lighting design. IALD members are required to achieve a minimum level of experience and recognition within the field. For more information about IALD, visit their Web site at http://www.iald.org

IESNA Recommendations and Standards

The Illuminating Engineering Society of North America (IESNA) is the organization in the United States that develops standards of illumination. Many IESNA standards have become American National Standards by meeting the requirements of the American National Standards Institute (ANSI). One of the most important IESNA standards is the recommended manner for selecting illumination levels.

Chapter 10 of the *IESNA Lighting Handbook, 9th Edition* provides a procedure for lighting design that emphasizes both lighting quality and quantity (lighting levels). The IESNA procedure utilizes a chart that lists building types and lighting situations (or "tasks"). It's similar to previous IESNA illuminance selection charts because it recommends lighting levels for specific tasks. However, it identifies other

[1] More information on the lighting certification process, and a list of certified practitioners, can be found at http://www.ncqlp.org.

"design criteria" by importance and directs the reader to other places within the *Handbook* where additional information is provided. The new procedure is not based solely on illuminance and contains considerably more information on other design criteria than previous versions. Lighting design implicitly requires balancing human needs such as visibility, mood and aesthetics with cost and efficiency. Recognizing lighting as more than just illumination is an important step toward lighting quality design.

The IESNA Lighting Design Procedure

The following lighting design steps are paraphrased from the *IESNA Lighting Handbook, 9th Edition:*

- Go to the Handbook's *Design Guide* chart and find the location or task under consideration.
- Learn about the *Design Criteria* that are Very Important, Important, and Somewhat Important for the specific lighting problem.
- Go to the section *Discussions of Design Issues* to understand every *Design Criterion*.
- Go to other chapters for discussions of how to apply the relevant *Design Criteria* and for a more thorough discussion of the issues that are only summarized in the *Design Guide*.
- Consult the section *Illuminance Selection* regarding the recommended horizontal and vertical illuminance. Use professional judgment to determine whether a change in these values is justified.
- Document the lighting design process.

The IESNA procedure is fundamentally based on human needs, in which lighting levels (footcandles on the work plane) are only a part. Chapter **2** of the *Advanced Lighting Guidelines* has a broader discussion on lighting for human needs.

IESNA publishes recommended practices and ANSI-approved standards for numerous lighting applications. These publications are shown in Table 3-8; for the most current publication list, refer to http://www.iesna.org.

Table 3-8 – IESNA Recommended Practices and ANSI Standards

Publication Title	Description
Daylighting	Discusses using daylight to illuminate spaces
Design Criteria for Interior Living Spaces/ANSI Approved	Describes lighting for residential living spaces and other interior spaces
Economic Analysis of Lighting	Discusses methods of lighting and why some method are more superior to others
Industrial Lighting	Recommended lighting for industrial environments
Lighting for Parking Facilities	Discusses requirements for a parking facility
Lighting and the Visual Environment for Senior Living/ANSI Trial Use Standard	Lighting for those with a visual disability
Lighting Casino and Gaming Facilities/ANSI Approved	Discusses lighting needs and regulations for casinos and gaming facilities
Lighting for Educational Facilities	Addresses recommended lighting for educational facilities
Lighting for Exterior Environments	Discusses the challenges of outdoor lighting
Lighting for Hospitals and Health Care Facilities/ANSI Approved	Provides guidelines for lighting health care facilities
Lighting for House of Worship	Discusses interior and exterior lighting for houses of worship
Lighting Merchandising Areas (expected November 2000)	Addresses retail lighting
Marine Lighting	Addresses the lighting needs of commercial and military vessels
Museum and Art Gallery Lighting/ANSI Approved	Covers museum and gallery lighting from many perspectives
NECA/IESNA Recommended Practice for Installing Indoor Commercial Lighting Systems/ANSI Approved	Describes installation procedures for lighting systems commonly used inside commercial and retail buildings
NECA/IESNA Recommended Practice Installing Exterior Lighting Fixtures/Submitted to ANSI for approval (expected October 2000)	Describes installation procedures for lighting systems commonly used in outdoor applications
NECA/IESNA Recommended Practice Installing Industrial Lighting Systems/ANSI Approved	Describes installation procedures for lighting systems commonly used in industrial and storage buildings
Nomenclature and Definitions for Illuminating Engineering/ANSI Approved	Lighting terms and symbols defined
Office Lighting/ANSI approved	Lighting the modern office environment
Photobiological Safety for Lamps and Lamp Systems-General Requirements/ANSI Approved	Covers the evaluation and control of optical radiation hazards from all electrically powered sources
Photobiological Safety for Lamps and Lamp Systems-Measurement Systems/ANSI Approved	Addresses the photobiological safety of lamps and lamp systems
Photobiological Safety for Lamps and Lamp Systems-Risk Group Classification and Labeling/ANSI Approved	Covers the classification, labeling, and informational requirements for all electrically powered sources of optical radiation
Roadway Lighting/ANSI Approved	Provides the design basis for lighting roadways, adjacent bikeways and pedestrian ways
Sports and Recreational Area Lighting	Addresses lighting design and equipment for recreational areas
Tunnel Lighting/ANSI Approved	Addresses the needs and variables for tunnel lighting

4. LIGHTING DESIGN CONSIDERATIONS

This chapter, Lighting Design Considerations, and chapter **5**, Applications, discuss the methods and tools needed to produce integrated lighting applications that use advanced sources, luminaires and controls. This chapter reviews the lighting design process, including issues of lighting quality as well as lighting levels (quantity), and presents a series of nineteen guidelines for designing advanced lighting systems. This chapter also reviews advanced tools and computer programs to assist designers. Chapter **5** provides examples of advanced lighting applications for private offices, open offices, executive offices, classrooms, several types of retail spaces, and an outdoor application. These examples demonstrate how advanced technologies can be integrated (with daylighting in some cases) to produce very efficient and quality applications.

4.1 The Lighting Design (and Redesign) Process

"Design" is the science and art of making things useful to humankind, and lighting design is the application of lighting—including daylight when it is specifically used as source of lighting—to human spaces. Like architecture, engineering and other design professions, lighting design relies on a combination of specific scientific principles, established standards and conventions, and a number of aesthetic, cultural and human factors applied in an artful manner.

In recent years, the field of lighting has been struggling with two prominent forces, *energy efficiency* and *lighting quality*. Just as the profession of lighting design began to emerge, in which the quality of lighting is held in high esteem, energy efficiency also became a concern in the design of buildings. Lighting designers initially faced the choice between attractive, well-lighted spaces and spaces that used a minimum of energy. The last quarter century has seen at least some resolution of this dilemma: dramatic improvements in lighting equipment technology, and maturation of the lighting design profession, each permitting better lighting designs that use less energy than previous practices.

The pursuit of more energy-efficient lighting dominated the lighting field from 1975–1990, creating awkward dilemmas for lighting designers. Fueled by utility rebates and commodity pricing, new lighting systems were designed to use minimum power. Existing lighting systems were "retrofitted" to save energy. Lighting installations of inferior quality were the rule, rather than the exception.

Many see the1990s as a period in which the quality of lighting made a significant comeback. This was most evident as the new century approached in a new process for lighting design put forth by the Illuminating Engineering Society of North America (IESNA), the major technical association for lighting in North America. IESNA's recommended procedures for lighting design are described in section **3.3.4**.

The *Advanced Lighting Guidelines'* mission is to describe lighting technology and techniques in order to encourage advanced designs that provide quality lighting with minimum environmental impact. While the IESNA procedure should generally lead to good quality lighting, it doesn't give energy efficiency and environmental impact a priority. The advanced strategies described in this chapter enhance the IESNA procedure so that it may be used to produce designs that minimize energy use and improve the sustainability of projects.

4.2 Lighting Quantity

4.2.1 Setting Criterion Illumination Levels

The IESNA design procedure described in section **3.3.4** is the most widely used and accepted method for determining lighting levels for applications. The method consists of the following:

- Choose an acceptable illuminance according to categories A through G, with A being the lowest and G being the highest. For instance, the illuminance associated with Category D is 30 footcandles.

- Adjust the actual design level according to tasks and human factors. The designer is strongly encouraged to make informed adjustments to the criterion light level. For instance, in Category D, one might choose 20 footcandles for schoolchildren and 50 footcandles for seniors. To make the correct adjustment, the designer should be aware of the occupant's age, the specific tasks to be performed in the space, and the extent to which daylight affects the space. The presence of other tasks, like a computer or adjacent workstation, also needs to be taken into account.

The determination of lighting level is critical. Choose levels too low and the success of the project may be at stake; choose too high, and too much money is spent and energy is used needlessly.

IESNA task illumination recommendations are for the design of lighting under ordinary circumstances, including the assumption that the viewer is "day adapted." The human eye is highly adaptive, so the precise illumination level is not critical. Increasing the illumination level by 100%, either by design or by the addition of daylight, will generally make a small improvement in visual performance. Decreasing the illumination levels will generally cause a reduction in visual performance, but dropping the light level in half will usually not make a big difference as long as the light quality remains good. Small differences (less than 25% difference) in light levels are more or less meaningless with respect to visual performance.

Other factors to take into account include:

- The adaptation level of the viewer. When "night adapted," a person typically will need lower overall light levels than when "day adapted." (See section 2.1.7 for more about day and night adaptation.)
- The viewer's age. The natural aging of the human eye reduces visual acuity and increases sensitivity to glare. Higher light levels greatly help visual acuity, as long as glare is controlled. Choosing light levels at—or sometimes above—the top level in the range is generally called for in designing facilities for seniors.(For more about the aging eye, refer to section 2.1.6.)
- The visual size of the task. Very small tasks, measured in visual angle according to the procedure, may require higher light levels; very large tasks may require lower light levels. (See section 2.1.3 for more about visual size.)
- The interaction of tasks. The specific needs of adjacent tasks may appear to be in conflict, but recognizing that light level recommendations are not absolute can make resolving these issues easier. For instance, many jobs involve computers (Category C) and paper tasks (Category D or E). Designers may use a task-ambient lighting design (see section 4.3.1) or dimming controls (section 8.2) to achieve an acceptable compromise.

Example: Choosing the Lighting Level for a Cafeteria

Consider the lighting for a cafeteria (Category C, 10 footcandles). In a college, the designer might choose Category D (30 footcandles) instead because the cafeteria also serves as a study hall. In a middle school, it would be reasonable to choose 20 footcandles of task illumination because of (generally) youthful eyes. However, in a retirement facility, the designer might choose a light level as high as 50 footcandles after reviewing recommendations for this specific type of facility, especially IESNA RP-28.

Advanced Guideline – Dynamic Light Level Selection

... design lighting systems that are based on a dynamic, rather than a static, model of vision and natural light

Ultimately, the designer chooses an appropriate static light level that does address the potential for varying the light level based on user preference, time of day, weather conditions and other factors. If electric light levels can be varied, there is a significant potential for energy savings as well as other beneficial effects. As an advanced guideline, design lighting systems that are based on a dynamic, rather than static, model of vision and natural light. With the ability to modulate light levels, appropriate electric light energy is used at all times, maintaining a minimum necessary light level and therefore, a minimum necessary lighting energy consumption.

For example, imagine a private office with a south-facing window. Most days, the amount of natural light exceeds the 30 footcandles of task light recommended by IESNA for office paperwork. The office may actually average 100 to 300 footcandles, and electric light may be unnecessary. However, on particularly dark cloudy days and at sunrise and sunset on clear days, it's necessary to maintain these task light levels with electric lighting. Later in the evening, a lower task light level may be acceptable, and by the time people arrive to clean the office, task light probably isn't needed, and the ambient light level may be reduced to 3 footcandles. And most importantly, when the space is vacant, the lights should be turned off. See Chapter 5 for examples of lighting designs in private offices with windows.

Example: A Dynamic Criterion for a School Cafeteria

In the example above (Choosing the Light Level for a Cafeteria), a criterion of 20 footcandles was selected for a school cafeteria.

Taking into account the varying needs of the cafeteria, set the following light levels using dimming and dynamic balancing:

Any occupied use between sunset and sunrise, 3 footcandles (basic orientation) with manual override to 20 footcandles

Between sunrise and sunset, 20 footcandles with electric light dimming and shutoff in daylit zones.

Increased illumination for serving and bussing area during meals, 30 footcandles.

4.2.2 Illumination Levels Based on Light Source Spectrum

Illumination recommendations based on lumens and footcandles don't completely account for certain effects of the spectrum of light sources. There are a number of conditions under which details of the light source spectrum need to be considered to better reflect human vision or perception. This has surfaced as two major concerns, one regarding interior lighting at typical indoor light levels, and the other for low levels of exterior electric lighting at night. They are discussed below.

Advanced Guideline – Interior Lighting Spectrum

The first concern centers on the optics of human vision. It has been demonstrated (Berman 1992) that the diameter of the eye's pupil is set by the response of the rods even at typical interior light levels, rather than the by the cones that are responsible for focal (or foveal) vision. Rod response is generally associated with scotopic vision (night vision), but at the modest levels of light used for interior illumination, it appears that rods remain active and control the size of the optical aperture or pupil. Pupil size affects both visual acuity and depth of focus.

. . . S/P ratios can be used to determine the relative sense of brightness from different sources . . .

The pupil of the eye becomes relatively smaller in response to light sources that are enhanced in bluish-green light, the portion of the spectrum where rods are most responsive. Because the pupil size effect relies on rod response it is referred to as a scotopic effect. A smaller pupil allows vision to have a larger range of focal distance. The increased range of focus also means that less accommodative effort of the eye is needed to bring close objects, such as reading or handwork, into focus.

Visual acuity is improved with a smaller pupil. Although the smaller pupil allows less light into the eye, at typical interior light levels it blocks the aberrant light rays passing through the outer edge of the lens where optical quality is poorer.

Berman's research makes use of factors called Scotopic/Photopic ratios, or S/P ratios. They are independent of light level and express a property of the light or lamp spectrum and express the extent to which a lamp favors scotopic effects. Sources with larger S/P ratios (such as high color temperature fluorescent lamps) can be expected to permit a greater depth of field and better acuity than those with smaller S/P ratios.

Table 4-1 – Scotopic/Photopic ratios for Indoor Lighting Applications
Shows many common light sources. Source: Berman 1992.

Light Source	Scotopic/Photopic Ratio (S/P ratio)	Light Source	Scotopic/Photopic Ratio (S/P ratio)
Low-pressure Sodium	0.20	4100°K Fluorescent (RE741)	1.54
High-pressure Sodium (35W)	0.40	4100°K Fluorescent (RE841)	1.62
High-pressure Sodium (50W)	0.62	5000°K Fluorescent (RE850)	1.96
Clear Mercury Vapor	0.80	Metal Halide (Thallium/Dysprosium/Holmium)	2.10
Warm White Fluorescent	1.00	6500°K Fluorescent (RE865)	2.14
White High-pressure Sodium (50W)	1.14	Daylight Fluorescent	2.22
Incandescent (2850° K)	1.41	Sun (CIE D55 Illuminant)	2.28
Cool White Fluorescent	1.46	Early Sulfur lamp	2.32
Metal Halide (Sodium/Scandium)	1.49	Sun + Sky (CIE D65 Illuminant)	2.47
Quartz Halogen (~3200° K)	1.50	7500°K Fluorescent lamp	2.47

In addition, the apparent brightness of a scene illuminated by white light is influenced by color temperature. Compared to low color temperature sources, high color temperature sources produce spaces that seem brighter. In general, a light source with a high S/P ratio will likely appear brighter for a given foot-candle level than one with a lower level. The S/P ratio of sodium/scandium metal halide, for example, is 1.49. Compared to high-pressure sodium (S/P ratio 0.62), the metal halide lamp could be expected to appear brighter. However, remember that brightness is not a measure of visual acuity or performance, and the effect of a “brighter” source may be undesirable for many reasons.

The primary potential benefit of this work is that we might be able to use spectrally optimized light sources that permit lower energy consumption levels. Because designing interior lighting systems with a low power density generally means using lower general and ambient light levels, use of sources with higher S/P ratio might provide both greater sense of brightness and in some cases better visual acuity and depth of field. However, while there is a growing consensus that scotopic effects are important, scientists and researchers still disagree on the extent to which S/P ratios or other factors might be applied to current standards for proper lighting.

As an advanced guideline, S/P ratios can be used to determine the relative sense of brightness from different sources, and in some cases, to predict acuity and depth of field benefits. But using S/P ratios to justify dramatic differences from conventional practices, such as using them to allow significantly lower light levels than IES recommendations, is currently **not** recommended. From the standpoint of visual acuity and performance, the current system of lumens and footcandles still serves to properly set light levels, and S/P ratios can**not** be used to change design practice in this regard.

Advanced Guideline – Non-Central Vision and Brightness Perception for Large Visual Fields

Consider using a lumen correction factor between 1.2 and 1.4 for modern mercury-arc white light sources . . . as compared to high-pressure sodium

The other primary concern centers on outdoor electric lighting at night. Traditionally, lumens, footcandles and other photopic quantities have been applied to nighttime exterior lighting conditions. This is correct only if the visual task is viewed directly forward. When the visual task is non-central or the perceived brightness of a large field of view is experienced (10 degrees or greater), then both rod and cone responses contribute to vision. Rod related vision (scotopic vision) is significantly more sensitive to blue-green light (507 nm) than yellow-green light (555 nm), the peak sensitivity of day vision (photopic vision). This combination of photopic and scotopic vision, called Mesopic vision, occurs at light levels typically found in outdoor lighting situations such as streets and roadways, parking lots, walkways, and sidewalks. Since the lumen is based on the spectrum of photopic vision, it is now recognized that without a spectral correction factor, lumens and all related factors (footcandles, lux, etc.) at light levels below 1.0 footcandle are not likely to provide a full representation of human perception.

Additionally, it is widely agreed that human peripheral vision at Mesopic light levels has both rod and cone responses. Studies at a luminance level of 0.1 cd/m² (Rea et al. 1996) have shown that the off-axis reaction time to peripheral movement under metal halide light, which has substantial blue content, is 50% faster than under high-pressure sodium light of the same footcandle level. This research, while still controversial, suggests that scotopically efficient sources may be preferred for many outdoor lighting situations, especially where threats from the side are an issue, such as personal security, crossing traffic, or animals crossing a highway at night.

Because of the renewed concern over the different spectral responses of rods and cones, it appears very important to consider the spectrum of the light source in outdoor lighting. As an advanced guideline, when off-axis detection and/or large field brightness perception is the primary concern, consider using a lumen correction factor varying between 1.2 and 1.4 for modern mercury-arc white light sources (metal halide, fluorescent, compact fluorescent, or induction lamps) as compared to high-pressure sodium. In other words, when applied at very low light levels a 10,000-lumen metal halide lamp appears to produce the same effective non-central exterior visibility as a 12,000 to 14,000-lumen high-pressure sodium lamp.

Researchers and scientists don't yet agree on how to apply spectral factors to outdoor lighting standards. For this reason, it is **not** recommended that lighting level standards or lighting calculations be changed to account for the affects of different light sources. However, if research in spectral response continues on its present course, the impact may be significant. Most importantly, sodium-based light sources, although more "energy efficient" as measured in lumens per watt, might no longer be considered the most "visually" efficient for outdoor lighting. This in turn might result in new lighting systems and light sources for the majority of parking lot, parking garage, industrial, warehousing and roadway applications where high-pressure sodium has been the preferred source for the last few decades.

4.3 Lighting Quality

Lighting profoundly affects many human reactions to the environment. These human reactions range from the obvious, such as the dramatic beauty of an illuminated landmark or the emotional response of a candlelight dinner, to subtle impacts on worker productivity in offices and sales in retail stores. (This range of human reaction is discussed in more detail in chapter 2.) The profession of lighting design, which grew from a mixture of theatrical and architectural methods, is largely valued for its ability to intuitively and artfully provide high quality lighting, at least for projects in which appearance and "mood" are very important.

An important recent trend in lighting philosophy and research is the concept that lighting quality often plays an equal, if not dominant role, to lighting quantity. However, lighting quality is highly elusive. Despite numerous attempts to create metrics of lighting quality, lighting quality remains a combination of measurable physical quantities, placed together in a particular order that is highly dependent on numerous factors involving space, finishes and activities. The current challenge for researchers is to provide more objective metrics of lighting quality to make it possible for more successful projects of all types.

The design procedure recommended in the ninth edition of the *IESNA Lighting Handbook* is based substantially on lighting quality. It embodies the current beliefs and findings about lighting quality in a manner that varies according to building type. Following the IESNA procedure is highly recommended, for at a minimum it helps the designer place the proper priorities on lighting quality as a function of space. But, unfortunately, following the procedure perfectly still cannot guarantee good lighting.

This is the dilemma facing every designer. One can design good quality lighting and yet not achieve "good lighting." Boyce (1996) helps us understand the difference by describing lighting in three quality categories:

- Bad lighting, where the lighting system suffers from a quality defect

- Indifferent lighting, where the lighting system has no quality defects
- Good lighting, where the lighting system is technically correct and excites the spirit of the viewer

A space with "indifferent" lighting quality should be the minimum design criterion for all lighting installations because any of the causes of "bad" lighting can affect worker performance.

This section provides numerous advanced lighting guidelines for the lighting design criteria identified in the *IESNA Lighting Handbook, 9th Edition.* These criteria have been organized in three general categories:

Light Distribution, including:

- Task and ambient lighting
- Daylighting integration
- Light pollution and light trespass

Space and Workplace Considerations, including:

- Flexibility
- Appearance of the space and luminaires
- Color appearance
- Luminance of room surfaces
- Flickering light
- Direct glare
- Reflective glare

Lighting on People and Objects, including:

- Modeling faces and objects
- Surface characteristics
- Points of interest
- Sparkle

4.3.1 Light Distribution

Task and Ambient Lighting Overview

The most common lighting design for commercial spaces has long been general lighting, in which a single type of luminaire is laid out in a more-or-less regular grid or pattern, producing relatively uniform illumination throughout the room. General lighting, however, was developed and promoted in the past based on an office norm of typing pools with no partitions in open office areas. With the advent of systems furniture in the 1970s, task lights became an integral part of the office workstation. By far the most common is a fluorescent luminaire attached to the bottom of a bookcase, binder bin or shelf. Many variations on the concept have evolved since the 1970s, including luminaires with variable screens designed to reduce veiling reflections. This type of task light remains a common part of office workstation design.

Task lighting systems independent from the space's general lighting systems are also found in other building types. For instance, the display lighting in retail stores is a form of task lighting. Similarly, task lights are used in industrial manufacturing and assembly, health care, residential lighting, and many other interior lighting applications.

However, task lights can't light the balance of the room, and thus some other type of lighting system is needed to produce the ambient illumination in the room. There are many options, including indirect luminaires mounted atop cabinetry or workstations, suspended luminaires, and recessed luminaires of the type usually used to produce general light (refer to chapter 7 for detailed information about luminaires). The key difference between general light and ambient light is that ambient light is designed to provide approximately 33% to 67% of the illumination level that would have been produced by a general lighting system.

Task-ambient lighting strategies produce energy savings in three ways. First, locating the light source close to the task most efficiently produces the illumination levels needed for the task. Secondly, task illumination levels don't have to be maintained uniformly though out the space, so ambient levels can be lower. And finally, some occupants won't use their task lights, and empty offices or workstations with absent occupants don't have to be fully illuminated, saving even more energy.

Advanced Guideline – Ambient Requirements

Design ambient lighting to illuminate the majority of the space to about one-third the task illumination level

The intent of ambient lighting is to illuminate the majority of the space to about one-third the task illumination level. In reality, this means providing an ambient light level of around 20 footcandles (200 lux). This is enough illumination to permit casual task work in most environments, and relates well to most task types requiring 50–60 footcandles of task illumination.

In spaces that are subdivided by office partitions, store fixtures or other relatively tall elements, it's important to ensure that the effect of the partitions is taken into account. Typical office partitions, for example, employ finishes with around 40% reflectance and stand approximately 55 in. tall. Their net effect is to reduce the average ambient illumination level by about 30% to 35%. Thus, an ambient lighting design producing about 30 footcandles average illumination in an empty room is often prudent.

Ambient light shadowing and uniformity are also issues. Using common troffers, a downlighting system producing 30 footcandles, average, will exhibit extremes of light and shadow when used in conjunction with office partitions. Some cubicles will receive over 50 footcandles from the overhead lighting system, and some will receive less than 5 footcandles. A negative result is very bright surfaces within the cubicle having a troffer overhead. An overly lighted office worker, especially one wearing light-colored clothing, can produce severe veiling reflections in the computer screen. Individually dimmable troffers can alleviate this condition. (For more about veiling reflections, see Advanced Guideline – Reflected Glare; for more about downlighting systems, see sections 7.5.2 through 7.5.7)

Indirect ambient lighting has often been advocated because of its good uniformity. An indirect lighting system producing an empty room level of 30 footcandles will tend to provide a comfortable light level for a range of workers and tasks. However, indirect lighting systems require higher ceilings than troffers, and suffer other drawbacks including possible additional cost, some lack of flexibility, and limited usability as task lighting. Section 7.5.8 covers indirect lighting in detail.

Other forms of ambient lighting shouldn't be overlooked. Wall-washing and wall slot "grazing" light produce ambient light indirectly from the wall surface (see section 7.5.3). In a gymnasium with a light maple floor, for example, downlight from the overhead lighting system will reflect upwards, illuminating the ceiling and upper walls.

And of course, natural light sources typically produce ambient light, at least for a portion of the space. Daylighting can be an excellent source of ambient light, especially if it's designed to provide balanced, uniform illumination throughout a space. For more about daylighting integration, see Daylighting below.

Advanced Guideline – Task Requirements

… provide task lighting that is under the control of each worker

Task lighting requires concern for the direction and intensity of the light, as well as the amount of illumination (footcandles). This is because many tasks exhibit specular reflections that can affect contrast. For example, gloss coating on magazines and books or pencil on paper can cause sufficient reflection to make it impossible to distinguish dark areas on a white background. The reader must constantly move the task (or his or her head) to eliminate the veiling reflections.

All tasks exhibit some degree of specularity (shininess), and as described in Advanced Guideline – Reflected Glare, the ability to see the task may be dramatically affected by the direction of the incident light. With highly specular tasks, or tasks viewed against a highly specular background material, the geometry of the source/task/eye relationship may be modified to improve visual performance. A typical situation is reading a glossy-page magazine under bright lights or outdoors. At certain angles, the reflected glare of the light source makes the print unreadable. Changing the location of the magazine, the viewing angle of the eye, or other physical movements solve the problem. As an advanced guideline, provide individual task lighting that is under the control of each worker, so that the individual worker can control both when it is used, and its placement, thus source/task/eye geometry.

As a general rule, light to the sides of tasks produces maximum visibility, while light to the front of the task produces maximum reflected glare. This basic axiom suggests orienting luminaires parallel to the direction of view, and to the sides of the viewer. But because not all lighting systems can be moved as desired and not all tasks can be placed where the lighting works best, compromises can be addressed through careful analysis.

As an additional advanced guideline, consider employing computer analysis that predicts visibility using metrics like equivalent spherical illumination (ESI) or relative visual performance (RVP) for fixed tasks under fixed illuminance sources. These metrics were developed specifically to analyze this situation, but unfortunately, are only useful for flat tasks in the horizontal plane, with a fixed viewing position and one of very few printed tasks. Nonetheless, for the design of certain work environments under fixed lighting conditions with demanding tasks, this remains a competent tool.

Task Lighting Example

In a private office, providing 50–60 footcandles of general light requires about 1.2 W/ft² of power using modern lighting technology. Providing ambient light of 20 footcandles requires only about 0.4 W/ft². If two task lights employing a 30-watt compact fluorescent lamp are used in a 100-ft² office, the total load will only be 1.0 W/ft², saving 0.2 W/ft². Moreover, the worker has additional control, and many will choose to turn off the overhead lights, especially if they also have a window, saving another 0.4 W/ft². Yet the worker retains task light levels where needed, sacrificing balanced luminance in favor of a more appealing atmosphere and customized personal space. See chapter 5 for additional task lighting examples.

Some tasks, such as a lifeguard viewing swimmers in a pool, may suffer from serious problems of disability glare caused by windows or skylights at certain times of day. To assess this type of problem, consider using the rendering functions of lighting software tools like Lightscape and Radiance. These programs are capable of dramatically demonstrating reflected glare, and although potentially laborious to do, permit the comparison of alternative lighting systems (including windows and skylights). Computer analysis tools are discussed in section 4.4.

Advanced Guideline – Light Distribution on Surfaces

Avoid distinct patterns, especially patterns that are irregular or harsh.

Keep most surfaces within a luminance ratio of 3:1

Lighting design ought to consider strategies for illuminating room surfaces, but in the majority of basic lighting installations, luminaires cause light to fall onto room surfaces somewhat randomly. For instance, direct luminaires with sharp cutoff, such as parabolic troffers and specular downlights, create distinctive "scallop" patterns on adjacent walls. Uplights can cast spotty pools of light onto ceilings, especially when luminaires are installed at the minimum suspension length. Track lights and wall-washers, when not uniformly installed, can create hot spots and unusual patterns. (For more about light distribution patterns for specific luminaires, see chapter 7.)

The IESNA procedure suggests that distinct patterns, especially patterns that are irregular or harsh, be avoided. Patterns in general are considered a problem, and keeping surfaces within a brightness ratio of 3:1 is suggested to minimize the impact of patterns of surface luminance.

As an advanced lighting guideline, designers should first review their designs for potential lighting patterns. Clues to potential problems include:

- Directional luminaires such as troffers and downlights that tend to create scallop patterns when near walls
- Uplights within 2 ft of the ceiling (unless specifically designed for a close-to-ceiling application)
- Poor balance of light (ceiling, wall or floor much brighter than each other)
- Walls and ceiling grids that aren't aligned, with varying spacing of luminaires to walls
- Wall-washing and accent lighting that is improperly located (too close to wall)

Most modern computer programs can reveal potential pattern problems. Should any of these situations occur, study the entire surface of concern with a point-by-point or rendering program. Using aesthetic judgment, correct any problems before completing the design. This may be quite difficult in some cases, such as those using suspended indirect lighting and relatively low ceilings. Be prepared to change the lighting design quite a bit to eliminate this problem. Refer to section 4.4 for information about computer programs for lighting design.

In buildings employing daylighting, use daylight for wall-washing, not just general illumination. Daylight can provide one of the best sources of even, vertical surface illumination. The best way to achieve this is to make sure that any daylight aperture, whether window or skylight, is directly adjacent to a perpendicular surface, as described in Advanced Guideline – Direct Glare. Skylights or windows located next to walls provide a very gentle and attractive wash of light across a large surface, up to three to four times the dimension of the aperture. Roof monitors can provide very even illumination across a sloped ceiling, as can windows that abut the surface of a ceiling. Louvers, blinds or lightshelves can also be designed to help distribute daylight evenly across a surface. For more about daylighting, see Daylighting below, as well as section 7.4.

Advanced Guideline – Light Distribution on Task Place (Uniformity)

Almost no lighting system provides completely uniform, even illumination. Early illumination engineering held out an ideal of perfectly uniform illumination in a space. There was little discussion or appreciation of the variability of lighting within space or time. The establishment of a target average illumination, such as 50 footcandles, was often misinterpreted to mean that a minimum of 50 footcandles would be provided over every square inch of a space.

Design ambient lighting so it ranges within plus or minus one third of the target level …

In the IESNA procedure, the variation of illuminance levels is recognized. For instance, if the target illumination level is 30 footcandles, this is considered essentially met if 67% or more of the task locations have at least 25 footcandles. This will help designers and inspectors better understand the relatively small significance of exact footcandle values.

As an advanced guideline, it's an essential concept that illuminance levels will vary within a certain range. Overlighting tasks is one of the greatest wastes of lighting energy, and many designers have erroneously sought to achieve the IESNA's recommended illuminance level as the minimum, not the average. Consistent with the IESNA procedure, study all task illuminance values to ensure that they are at least 2/3 of the target value. But likewise, note task locations where illumination is more than 4/3 of the target value. If possible, change lighting until more than 90% of the task locations are within the range of the target, plus or minus one third (range 67%–133%).

As part of this process, it's important to identify the difference between "task" and "ambient" illumination (also see section on task and ambient lighting, above). Providing task level illumination should be limited to actual task locations, not averages throughout a room. The ambient light level should be at least 1/3 of the task level, up to the target illumination level defined for that space. By providing ambient light that is typically between 1/3 and 2/3 of the target level, and task light between 2/3 and 4/3 of the target level, a space generally is using the least amount of electric light energy and still meeting IESNA recommendations.

Example: Uniformity in Small Private Office

This example shows alternative means of providing adequate light levels in a small private office, assuming an office size of 12 ft x 9 ft (108 ft²), 80/50/20 reflectances, illumination from two 2 x 4 lens troffers. Based on a target task illumination of 50 footcandles:

Using the lumen method, a standard design in which each luminaire with two T-8 lamps and standard electronic ballasts produces 45 footcandles, the average throughout the room is 1.11 W/ft².

Using point calculations and maintaining at least 17 footcandles ambient lighting (50 x 1/3) and at least 33 footcandles task lighting (50 x 2/3), the recommended IESNA lighting levels can be provided using tuning (fixed dimming) or reduced ballast factor ballasts (60% ballast factor) at 0.76 W/ft², or 31% less than the standard solution.

Another means of providing adequate light levels would be to employ a single, ceiling mounted indirect luminaire with two T-8 lamps. It will produce a relatively uniform ambient illumination of 18–20 footcandles. Then a task light can be used to provide illumination on the task of 33–66 footcandles, which can be nicely done using a table lamp with a 30-watt compact fluorescent source, such as a circline or 2D lamp. The power density of 0.83 W/ft² is still 25% less than the basic, common solution.

Refer to chapter 5 for more office lighting examples.

Daylighting Integration

Daylighting is the practice of using windows, skylights and other forms of fenestration to bring light into the interiors of buildings, using various mechanical means to control the amount of daylight, and employing complementary lighting electric lighting systems (including controls). It is perhaps the most demanding and challenging form of illumination, because of its variability and even more so, because of its impact on many aspects of a building. In traditional modern building design, various disciplines tend to work independently: architects design the mass and fenestration, structural engineers design the structure, mechanical engineers design HVAC and electrical engineers or lighting designers design the lighting. To design daylighting properly, integration of design and coordination among disciplines is essential.

A number of sections of the *Advanced Lighting Guidelines* provide an excellent resource for learning and applying daylighting. Chapter 5 provides example applications employing daylighting design. For details about daylight as a light source, see section 6.3; for daylight systems, see section 7.4. Daylighting controls are discussed extensively in section 8.4.

There are, however, some basic observations that can help lighting designers, architects and engineers begin to understand the potential impact of lighting, and by thinking about daylighting as part of the lighting system, they can encourage the use of daylight in basic building types where the benefits can be realized with relative ease.

The Principal Benefits of Daylight as a Light Source

Recent studies have provided at least some scientific evidence that people respond positively to daylight: they feel better, they work better, they learn better. But even if this were not true, daylight enjoys a significant advantage to electric light. The spectral content of natural light produces about 2.5 times as many lumens per Btu of cooling load. And if introduced through modern high-performance glazing with a low-emissivity ("low-e") coating, which removes some of the infrared energy, natural light can produce almost three times more illumination for the same cooling load of electric light. So if daylight is employed that produces light levels comparable or even higher than electric lighting, and electric lights are extinguished, daylit portions of a day-use building can be illuminated by saving almost all of the electric lighting energy and about half of the energy needed to cool the building load created by the lights. Moreover, the savings tend to coincide with energy peaks on hot summer days.

Daylighting also has many other advantages that augment the lighting quality in a space, as discussed in section 4.3 – Lighting Quality. These include being a flicker-free, scotopically rich, full-spectrum light source, with excellent three-dimensional modeling characteristics. The fact that daylight varies can be an advantage, for adaptation problems in interior spaces are often caused by a person's moving between indoors and outdoors, and the interior ambient level in a daylight space should vary directly with the exterior light levels.

Placing Daylight in Lighting Terms

Daylighting in architecture tends to be employed by architects in pursuit of the aesthetics and human factors of daylight. Just having daylight is not energy efficient, even if electric lights are extinguished (and too often they are not). Like bad electric lighting, daylighting can introduce numerous lighting and energy problems. Lighting designers should at least check proposed daylighting schemes to ensure that the architectural design does not create problems.

The primary energy issue is introducing a controlled amount of daylight such that the additional cooling load of the daylight is less than the cooling load of electric lighting that is turned off or dimmed during daylight periods. As a rule of thumb, the average daylight illumination level under peak conditions should not exceed 3 to 5 times the appropriate electric lighting level for the space. Excessive daylight increases the cooling load for the space and requires larger more expensive heating, ventilating and air-conditioning (HVAC) equipment. In other words, in a space where an appropriate electric light level is 50 footcandles, having average daylight levels in excess of 250 footcandles is probably inefficient design. The point at which daylighting becomes an energy problem varies considerably depending on climate, architecture, and other factors, but designers should be aware of the potential problem.

It's also important to consider the quality of daylighting. Like electric illumination, daylight can cause disability glare, discomfort glare, and other problems. For instance, a skylight should be shielded, just as if one were using a downlight. A standard, commercial skylight 4 ft x 8 ft introduces more average lumens than a 1000-watt metal halide lamp. Think of the skylight well as the shielding of an electric luminaire. Likewise, employ a refracting lens or diffuser in the skylight to prevent hot spots of light in the room from direct sun. Remember that daylight control on the east, south and west exposures is critically important in controlling daily and seasonal light changes, especially the potential for glare. For more about shielding strategies for daylight systems, see section 7.4.

Advanced Guideline – Daylighting Integration and Control

Most buildings have some windows and other potential forms of daylighting. For example, classrooms can easily be designed to provide adequate daylight throughout most of the year. Winter mornings, rainy or snowy winter days, and evenings are the only time most electric lights should be needed in the average classroom (see examples in section 5.8). Similarly, most single-story commercial buildings could easily be daylit through the use of skylights. These daylight strategies can save substantial amounts of energy during peak daylight periods if the electric lights are reliably turned off. Occupants have been observed (Lowe, Rubinstein) to leave the electric lights off or choose lower output options if there is sufficient daylight in the space *when they enter* the room. However, for truly predictable energy savings from daylighting, the use of automatic photocontrols is needed. The presence of daylight does not deter the occupant of a space from turning on lights and defeating the system.

No energy codes in the United States currently require automatic daylighting controls, although buildings are required by most energy codes to provide separate switches for “daylit zones” to encourage occupants to harvest the savings. To date, photocontrols have not been considered sufficiently cost effective in all cases to make them a code requirement. However, the cost of dimming ballasts and photocontrols has been dropping rapidly in the past few years, making their use ever more attractive. Dimming ballasts offer the opportunity of other control strategies as well. There are a number of simple strategies that can be pursued now that will make daylight integration more widely successful. Future energy codes are expected to require dimming ballasts and automatic daylighting controls.

… for daylit workplaces with fluorescent lighting … equip every luminaire with a dimming ballast … or multilamp switching

Circuiting should follow the contours of daylight illumination in the space

As an advanced guideline for daylit offices and other workplaces with fluorescent lighting, the designer might begin by equipping every luminaire with a dimming ballast. Ballast costs are sufficiently low to make this worth pursuing, since daylighting, tuning (fixed light maximum) and dimming (adjustable light levels) are then possible. Any of the modern dimming ballast systems are probably acceptable if implemented with sensors and control circuits. However, if designing the building for future controls circuits, as in a tenant-occupied building, consider using the 0–10 volt dimming ballast as it presently permits the widest range of sensors from a variety of manufacturers.

As a budget option, at least consider using multilevel electronic ballasts that permit switching light levels using a simple switch circuit. Using multiple lamp luminaires and switching them to provide variable light levels is an excellent and cost-effective design strategy for many space types, especially large areas without stationary tasks. For instance, instead of HID industrial downlights in a daylit retail store, consider using downlights with multiple compact fluorescent lamps having separate ballasts.

The most important basic step toward daylight integration is to make sure that branch circuit wiring be designed to provide independent switch legs for each daylit zone. Circuiting should follow the contours of daylight illumination in the space. This will enable daylighting control to be provided at the lowest cost regardless of when the actual controls are added. See section 8.4.3 for more information.

For each project, seek out additional cost-effective and reliable ways to harvest daylighting savings. The key to success is designing a system that is reliable, simple and effective. A system requiring minimum commissioning is probably best, preferably a system that will work well right out of the box and will even improve if properly commissioned. Improvements to daylighting controls are rapidly evolving, and the advanced designer needs to stay abreast of the latest developments. Meanwhile, don’t be afraid to have a system that is not optimized—if it has the potential to be saving 70% but it is only saving 50%, use it anyway.

Advanced Guideline – Light Pollution and Light Trespass

Use night lighting only when and where necessary …

Use the minimum amount of light needed rather than the maximum …

Use sources with cutoff optics that restrict light to the intended area of illumination …

In outdoor lighting, an electric light usually illuminates more than just the intended area. Through lack of optical control or overlighting, stray light also illuminates adjacent properties. This light can become offensive if unwanted, and it has become known as light trespass. Once believed to be a minor problem usually involving tennis courts and commercial establishments in expensive neighborhoods, light trespass has become recognized as an area of significant concern and perhaps even future regulation.

In a related problem, electric lights emitting light upward or reflecting light upward cause a condition called light pollution. Light pollution causes moisture and particles in the air to glow at night. It creates the unfortunate sky glow of cities, obscuring the stars from view. See sections 3.2.4 and 3.2.5 for an overview of the environmental impacts of light trespass and light pollution, respectively. For a discussion of advanced outdoor luminaires, see section 7.6.

In the IESNA procedure, both light trespass and light pollution are recommended concerns for the lighting designer. As an advanced guideline, it's important to realize that both problems involve energy, and directly or indirectly pollute in a number of ways. Several steps should be taken to avoid or minimize light trespass and light pollution:

- Use night lighting only when and where necessary. Design exterior lighting to meet, but not exceed, the IESNA design guide. Overlighting directly contributes to light pollution and is often related to light trespass.
- Use the minimum amount of light needed rather than the maximum. Provide uniform lighting with good distribution that avoids wasteful "hot spots." Design for the lowest maintained illuminances that will produce the desired effects.
- Use sources with cutoff optics that restrict light to the intended area of illumination.
- In many cases, use more sources, each of lower wattage, to improve uniformity in the intended illumination area and minimize trespass into adjacent areas.
- Use sharp cutoff light sources and other means to eliminate light directed upwards or sideways. Consider "full cutoff" luminaires that emit no light above 90 degrees (horizontal). (It may be possible to reduce light pollution by using cutoff or semi-cutoff luminaires spaced farther apart than full cutoff luminaires can be spaced to achieve the same uniformity. This is controversial but deserving of analysis.)
- Use lighting strategies that allow nighttime adaptation of the eye to very low light levels. Unless security is an issue, focus on wayfinding with very small points of light, rather than illumination of large areas. In signage and retail, use color contrast to attract attention, rather than high levels of illumination.
- Use timers and occupancy sensors to limit the use of outdoor lighting to only the minimum time required for the purpose. Most outdoor lighting can be shut off or switched to a minimum level after 10 PM or 11 PM. Use astronomical time clocks or energy management system (EMS) controls to switch lights off, rather than simpler photocells that only switch lights on at dusk and off at dawn (see chapter 8).
- Consider a "layered" approach. This might involve one set of full cutoff luminaires that provides the low-level utilitarian lighting (for example, street lighting from tall poles spaced 120 ft apart), and another set of luminaires that produces more decorative effects or provides pedestrian-scale light (for example, traditional-style glowing post-top luminaires on 12 ft poles). The second set of luminaires can use low-wattage lamps, and can also be shut off at 11 PM, leaving the utilitarian lighting burning all night for security purposes.

- Avoid development near existing astronomical observatories; when outdoor lighting is unavoidable, apply rigid controls. Consult with the observatory on needs for specific spectral control and shielding.
- Locate outdoor lighting below tree canopies, not above. The leaves of the trees then shield the light from the sky.
- Provide reflective surfaces for lettering or other elements that need to be illuminated at night. Illuminate only the lettering, not the background.
- Light from the top down, rather than from the bottom up. In signage lighting and building facade lighting, consider lighting from the top to reduce stray uplight. Spilled light is at least reduced by reflection from the ground before it is directed to the sky.

Many cities have light pole height ordinances designed to prevent light trespass. In general, pole height is not the primary issue; rather, cutoff and shielding determine the quality and control of light. Avoid purely ornamental exterior luminaires, ordinary floodlights, and similar light sources that have a minimum of optical control.

4.3.2 Space and Workplace Considerations

Advanced Guideline – Flexibility

The preservation of lighting and daylighting systems throughout their useful life is an important measure of sustainability. The ability to rewire or reconfigure an office building as easily as a living room is often viewed as ideal. Furthermore, an advanced perspective recognizes that the "one-size-fits-all" approach to lighting can be very wasteful. Redundant systems that allow different uses of the space may save energy and materials over the long run.

Consider use of:

Easily re-configured controls
Portable luminaires
Modular wiring
Lighting tracks
Lightweight suspended luminaires

Advanced lighting designs should be flexible enough to ensure that:

- Lights operate where needed, and are off where not needed, as people move around within a space and use rooms in different ways. Lighting designs employing occupancy sensors and other methods of ensuring this flexibility are the most sustainable. Also, ensure that changes in tasks can be accommodated with changes in light level, through dimming, for example. Controls are discussed in detail in chapter 8.
- Spaces used for "hoteling"—the occasional or transient use of a workspace—remain dark unless needed. Hoteling requires lighting and controls that permit these workspaces to function independently of the remainder of the space, and generally requires a combination of control flexibility and design in which dark areas do not negatively influence ambient light quality in general.
- The lighting system can be rapidly reconfigured to match a changed floor plan or accommodate a different space use, and still operate at maximum energy efficiency. This philosophy suggests mechanical and electrical flexibility. Consider modular wiring and re-mountable lighting systems to attain this flexibility. Many manufacturers are developing "plug and play" lighting systems that feature this ease of reconfiguration. Also, consider using lighting systems that serve reasonably well in all anticipated uses so as to reduce the likelihood of needing a different type of luminaire when the reconfiguration occurs. Common troffers (lens and parabolic) are among these "jacks of all trades."
- The lighting system permits multiple uses and on-demand flexibility in multiple-use spaces such as conference rooms and modern A/V classrooms. Multiple separately controlled or dimmed circuits can allow sufficient flexibility to meet the room's various arrangements.

Most modern lighting systems intended for commercial use are designed to be as flexible as conventional lay-in ceilings and common wiring permit. Far too many luminaires are installed in inappropriate locations because they are perceived to be immovable or too expensive to move, when in fact the luminaire is wired by a flexible “whip” permitting relocation in a few minutes. Even track luminaires are usually not moved once installed. For more information about specific luminaires, see chapter 7.

To design lighting systems that achieve the desired flexibility, consider these options in selecting lighting systems:

- Employ a control system that is easily reconfigured and commissioned
- Use portable lighting equipped with a cord and plug
- Use a modular wiring system
- Use a lighting track or busway
- Use lightweight luminaires suspended from the ceiling

Advanced Guideline – Appearance of Space and Luminaires

In the IESNA design procedure, the appearance and style of the luminaire play a major role. Throughout the history of lighting, thousands of different types and styles of luminaires have been built. Architectural, interior design or landscape architecture issues typically limit luminaire choices to a particular style that is suitable for the project. Some lighting equipment has been utilitarian (like the keyless socket) but until the era of the recessed luminaire, most lighting equipment complied with the architectural style of the building. Modern projects may permit the designer greater latitude in selecting among recessed luminaires as well as more traditional luminaires.

… find lighting systems that embody the project’s style or aesthetic … while using high-efficacy sources and efficient principles

Luminaire efficiency and the ability to use efficacious sources have become increasingly important criteria for selecting luminaires. Once seen as a tradeoff between aesthetics and appearance, attractive traditional and contemporary luminaires are available at many price levels.

As an advanced guideline, the designer should be constantly challenged to find lighting systems that embody the project’s style or aesthetic, but to do so using high-efficacy sources and efficient principles. For instance, choose among decorative luminaires that “hide” the light source, such as a diffusing bowl. Avoid luminaires such as crystal chandeliers that require lamps with bare incandescent filaments—unless, of course, a replacement in appearance for the bare filament can be employed, such as an LED.

See chapter 7 for an in-depth discussion of luminaires.

Advanced Guideline – Color Appearance

… use light sources of CRI 80, or better…

… employ color balanced efficient alternatives to eliminate incandescent lamps

… work with higher color temperature and higher CRI sources to produce beneficial vision effects …

The appearance of color, both in terms of chromaticity (color temperature or degrees Kelvin) and color rendition (CRI), are important in the overall feeling of the space, and in some instances can have a dramatic effect on visual tasks. The IESNA design procedure requires the designer to consider both chromaticity and CRI as key components of a design. Section 6.2.4 covers chromaticity and CRI in detail; below is brief overview of design considerations related to color appearance.

Chromaticity

A preference for a narrow range of source color temperature has been established and appears to coincide with design practice. Known as Kruitof's Curve, in general the lower the ambient light level, the lower the preferred color temperature range. Most commercial illumination levels coincide with an acceptable color temperature range of 3000K to 4500K.

Color temperature preference may be affected by latitude. The color temperature of light can affect perceptions of thermal comfort. Modern practice in commercial settings in the United States, such as offices and grocery stores, appears to favor a cooler source (4100K) in the southernmost U.S., an intermediate source (3500K) in the majority of the country, and a warmer source (3000K) in northern states. By volume in T-8 lamps, the most popular color temperature is 3500K throughout the U.S.

This does not eliminate consideration of other color temperature lamps. As noted in section 4.2.2, high color temperature lamps tend to add "scotopic" benefits, and T-8 lamp products are available at 5000K and 6500K. In addition to scotopic effects, high color temperature lamps tend to better match natural daylight, which varies between 4000K and 7500K for most of the day. When used in a daylit space, warm color temperature lamps can appear noticeably pinkish or yellow in comparison to the daylight. But at night, the cool lamps may appear unnatural; this factor should be taken into consideration in the design.

Because fluorescent and compact fluorescent lamps can be obtained in matching colors, it's good practice to match light color whenever possible. This is generally extended to include 3000K halogen and metal halide lamps and 4100K metal halide lamps, which can generally be matched to fluorescent lamps of corresponding color temperature.

Color Rendering

Color quality is generally assessed using Color Rendering Index (CRI), a scale having a maximum rating of 100 for reference sources like natural daylight and laboratory-quality incandescent light (see section 6.2.4 for more about color rendering). Ordinary incandescent and halogen sources and unfiltered natural daylight are often CRI 100 (or extremely close). Designers should be aware that modern "high performance" windows modify the color of daylight, and both correlated color temperature and CRI can be affected. Specially tinted glazing such as green or bronze can produce dramatic color change with comparatively lower CRI. (See section 7.4.2 for more about tinted glazing.)

Most other electric light sources, especially energy-efficient sources, have CRI that is lower than 100. Current practice is to employ sources having CRI of at least 70 for most applications. Recent advances in fluorescent and HID technology make light sources of CRI over 80 quite practical; these should be employed whenever possible.

There are specific lamp products that produce light of extremely high CRI, in the range of 90–100. These lamps tend to be more expensive and have lower lumen output than 80–89 CRI lamps, so the relative benefit of their use is limited to special applications where critical color discrimination is required, such as fine art and graphics art studios, textile mills, etc.

Design Considerations

As a basic concept in energy-effective lighting, the designer should use efficacious sources in as many applications as possible. Color appearance has long been a major issue, as most people still associate fluorescent light with the unfortunate cool and greenish hue of “cool white” lamps. The key to more energy-effective design is to employ efficient full-size fluorescent, compact fluorescent, and HID lamps to create spaces balanced at various color temperatures in order to eliminate incandescent lamps. Whenever possible, however, a higher color temperature such as 4100K or even 5000K will permit realization of the scotopic effects.

Use Table 4-2 as a guide to color temperature selection for lighting designs using high efficacy lamps.

Table 4-2 – Preferred Color Temperature Ranges

Lamp CCT (Kelvin)	Applications
<2500	Bulk industrial and security (HPS) lighting
2500–3000 “Warm”	Low light levels in most spaces (<10 fc). General residential lighting. Hotels, fine dining and family restaurants, theme parks. Suitable high-efficacy sources include fluorescent and compact fluorescent, 2700K or 3000K and halogen IR lamps.
2950–3500 “Neutral”	Display lighting in retail and galleries; feature lighting. Suitable high-efficacy sources include halogen IR, white sodium, and ceramic metal halide.
3500–4100 “Cool”	General lighting in offices, schools, stores, industry, medicine; display lighting; sports lighting. Suitable high-efficacy sources include induction, fluorescent, compact fluorescent and metal halide.
4100–5000 “Very cool”	General lighting in offices, schools, stores, industry, medicine, and sports lighting. Also special application lighting where color discrimination is very important. Suitable high-efficacy sources include induction, fluorescent, compact fluorescent and metal halide.
5000–7500 “Cold”	Special application lighting where color discrimination is critical; uncommon for general lighting, Suitable high-efficacy sources include fluorescent, compact fluorescent and metal halide.

As an advanced concept, designers can work with higher color temperature and higher CRI to produce beneficial vision effects, which, in turn, may permit the selection of a lower overall illuminance level. But this must be carried out in a manner that does not destroy the ambience of the space. Using 4100K instead of 3000K or 3500K, for instance, will appear brighter and may produce slightly higher visibility, especially if the source is a rare-earth fluorescent or metal halide with significant blue output.

Ideally, although it is presently difficult to achieve, the color of electric light, as well as its intensity, would shift in a natural manner, following the patterns of daylight. The highest light levels would be provided by day at 5000K, dimming at dawn and dusk continuously down to 2500K or less before taking on a nighttime appearance. At low light levels, low color temperature sources appear most natural, especially for interior residential and hospitality spaces, but higher color temperature sources, like moonlight, offer better visibility.

Advanced Guideline – Luminance of Room Surfaces

… use light colored room surfaces and minimize the use of dark surfaces

… ensure that the average room surface luminance is at least 10% of the task background

Technically, luminance thoroughly describes the visual scene and should be the primary design metric. The problem is, luminance is not easily measured and calculations are complex and time consuming. Because luminance depends on the reflectance of the surface, it’s highly dependent on exact knowledge of architectural and interior finishes. Most footcandle-based standards are simplifications and approximations of true luminance-based design and analysis.

The IESNA design procedure recommends that luminance be considered as part of the design. As a basic premise, the design criteria suggest that wall and ceiling luminance be close to task luminance. The luminance of the task background—typically white paper—should be used as the basis and in general, room surfaces should be between 1/10 and 10 times this level, preferably less than the task.

Luminance, being a quality of the room surface as well as light, places critical elements outside of the lighting designer's hands. Periodic trends in interior design introduce dark paints and finishes. These trends contribute to difficulty in producing energy-effective design by increasing lighting requirements to raise surface luminance into the comfortable range.

As an advanced guideline, the lighting designer should:

- Encourage the use of high diffuse reflectivity (light colored) surfaces and minimize the use of dark surfaces. Work with building owners, architects and interior designers on this key issue to improve the efficiency and cost-effectiveness of the building.
- Use computer modeling to ensure that the average room surface luminance is at least 10% of the task background. See section 4.4 for information about computer modeling.
- With indirect lighting systems, use computer calculations to check for uniformity, and try to maintain 10:1 luminance ratio or better.

Example: Back Wall Illumination in Open Office

In open-office lighting design, the illumination of the interior or core walls is critical in producing balanced luminance. A typical off-white wall (70% reflectance) can be washed to a vertical illumination level of about 20 footcandles and will achieve a luminance level of about 1/3 the task luminance for ordinary paper tasks. However, if the wall were to be painted a saturated blue (7% reflectance), achieving the same level of luminance would require 10 times as much electric light energy.

For more examples of office lighting design, see chapter 5.

Luminance is also a concern with respect to computer screens. Extremely bright or unevenly lighted surfaces can cause unwanted reflections in CRT-type (cathode ray tube) computer screens. As with paint, the best solutions—flat-faced CRT screens or flat active matrix screens—are beyond the control of the lighting designer. For average situations with undefined monitors, a sufficiently bright wall can easily be a reflected veiling image in a computer screen. For this reason, wall luminance and uniformity can be an issue in the computer work environment. As a general rule, the upper wall luminance should match the ceiling luminance, or at least not be significantly different. See Advanced Guideline – Reflected Glare for more strategies for reducing reflected veiling images.

Light-colored walls and room surfaces greatly improve the efficiency of every lighting system, including daylighting. Luminous ratios between windows and walls can be greatly reduced through the use of light-colored walls, and by making sure that the window abuts a perpendicular wall. Windows that create a "punched hole" in a wall are the worst offenders of luminance ratios, and often require non-efficient measures to correct the poor lighting quality. The Daylight Systems section (7.4) discusses this issue in greater depth.

Advanced Guideline – Flicker and Strobe

The visual system has a range of sensitivities to flickering light, depending on illumination levels and the size of the flickering object. Above a certain frequency flickering light is perceived as steady. The focal system can detect flicker up to about 60 Hz (the critical fusion frequency), but the peripheral system can only detect flicker up to about 18 Hz, with a peak sensitivity at 15 Hz (IESNA 2000, 3-20).

… eliminate from consideration any light source that does not operate on DC, high frequency AC (greater than 30 kilohertz), or AC square wave

Flicker becomes the most troublesome when two cycling systems interact with each other to produce light modulations at frequencies approaching 15 Hz. This can happen with the interaction of computer screens or rotating equipment with electric lights that also have a strong oscillating light output. Oscillating light levels from a single fluorescent or HID lamp is most likely to be associated with these problems.

The degree of oscillation from a lamp is a function of lamp type, type of phosphor coating, lamp configuration, type of circuit, and type of ballast. Fluorescent and HID lamps on magnetic ballasts flicker at a rate that is twice the line frequency (120 Hz in the United States and 100 Hz in Europe and southeast Asia). Recent studies comparing office worker performance under various fluorescent lighting systems have found a small but noticeable improvement in performance under electronic ballasts over magnetic ballasts (Veitch 1998). This finding is consistent with the theory that a reduction in flicker, such as occurs with electronic ballasts operating at 20kHz or more, should improve performance.

There is some evidence that flickering lights can cause headaches and other problems in sensitive individuals (for more about possible health effects, see section 2.2.6). In some applications, flickering lights can cause dangerous conditions in work areas with rotating or moving parts. The *IESNA Lighting Handbook* makes a relatively broad condemnation of flickering lights.

As an advanced guideline, consider every possible way to eliminate flickering electric lights (except of course for signs and glittering lights, such as in casinos). For instance, eliminate from consideration any lamp or light source (other than incandescent) that does not operate on DC, high frequency AC (greater than 30 kilohertz), or AC square wave.

See sections 6.5 and 6.6 for more information about flicker and strobe effects associated with fluorescent and HID sources, respectively.

Advanced Guideline – Direct Glare

Direct glare is caused by a view of the light source, often with high contrast to the surroundings. While the bare light bulb is technically the most efficient “luminaire” because it has no internal losses, it’s a poor choice in almost every application because the glare from the bulb walls is visually disabling. Thus, the control and distribution of light from a source is an essential characteristic of its visual efficiency. Glare is associated not just with lamps, but also with daylight, especially when one is exposed to low angle, direct sunlight. Any excessively bright source, not just electric lamps, but also low-angle sunlight or overly bright luminance, can cause glare from windows or skylight diffusers. IESNA design guides promote modest ratios of brightness.

Be the most concerned about sources of glare in relation to stationary tasks …

As an advanced guideline, it’s important to understand that there is not a clear-cut line between comfort and glare. For instance, many people will happily work away in a daylit space with a window, turning their backs to the sun and avoiding the glare while generally enjoying a cheerful space. In other cases, people will tolerate some glare as long as it contributes to an overall impact of sparkle or a festive mood. Yet a modest difference in brightness caused by an unattractive source like a lens troffer is often deemed too much glare.

In other words, there is acceptable glare and unacceptable glare, and the definition is not quantitative but qualitative. In general, be more concerned about glare caused by fluorescent lamps, lenses, and other overly bright sources of manmade light. (Chapter 7 provides more information about glare issues related to specific types of luminaires.) Be less concerned about the glare of sunlight and small point sources like incandescent filaments. Be the most concerned about sources of glare in relation to stationary tasks when the building occupants cannot easily relocate themselves or their task.

The first most important step to avoiding glare in daylighting applications is to always arrange for a window or skylight to be next to a surface that will diffuse its light. Avoid “punched holes” in walls or ceilings. A window next to a wall will balance luminance ratios between indoors and out. A splayed skylight well will balance luminance ratios between the ceiling and the skylight.

… always arrange for a window or skylight to be next to a surface that will diffuse its light

Avoid "punched holes" in walls or ceilings

The second most important step to avoiding glare in daylighting applications is to balance the illumination levels in the space with a source of daylight from at least two directions. Very bright illumination from a window can be balanced by daylight from a window or skylight on the other side of the room. Redirecting daylight, through the use of blinds, lightshelves, or special glazings can also help to balance luminance ratios, and thus reduce glare. For further discussion of glare and daylighting, see section 7.4.

Balance the daylight illumination levels in the space with a source of daylight from at least two directions

Occupant control of light sources is also an important strategy in reducing the impact of glare. Adjustable task lights and individually dimming ceiling luminaires provide control over glare conditions from electric lighting. Individually controllable window blinds and curtains provide occupants with the opportunity to adjust lighting conditions to their particular needs and wants. When feasible, such personal control of lights will greatly reduce the negative impacts of potentially glaring sources. For more about controls, refer to chapter 8.

Advanced Guideline – Reflected Glare

Disability glare and veiling reflections have long been associated with gloss-coated paper, pencil paperwork and the computer CRT (cathode ray tube) screen. All can create specular reflections that can cause glare, either reducing comfort or disabling the worker’s vision in particular areas.

… modify the task to eliminate glare problems

Use a flat adjustable computer screen to eliminate specular reflections …

Indirect lighting, by creating a diffuse and uniform illumination, has been advocated as a solution to preventing reflected glare in workplaces. However, if properly located and shielded, direct lighting systems and especially, two-component lighting systems (see task and ambient lighting discussion in 4.3.1) may provide the best overall results in preventing reflected glare. Direct and indirect luminaires are discussed extensively in section 7.5.

As an advanced lighting guideline, after the lighting system has been optimized to minimize glare, consider modifying the task to eliminate any remaining glare problems. The computer CRT screen, for example, can be changed to a flat screen, either CRT or active matrix, to minimize or eliminate specular reflections from ceilings and upper walls. The angle of the screen can be adjusted to further minimize these problems (see sidebar below, Veiling Reflections in Computer Screens). Use of ink, rather than pencil, virtually eliminates reflected glare problems with paperwork. Use of matte-coated or uncoated paper, rather than gloss-coated paper, prevents glare reflections in printed material. Similarly, reflected glare from polished floors or shiny conference room tables can be avoided by changing the finish.

Lacking these options, the designer should utilize source/task/eye geometry studies to eliminate or minimize the impact of reflected glare (see Advanced Guideline – Task Requirements). In addition, pay close attention to room surfaces and finishes and either design light accordingly or change the finish (see Advanced Guideline – Luminance of Room Surfaces). For instance, unfinished or matte-finished wood can be wall-washed using relatively generic equipment, but if a satin or gloss finish is applied, a more sophisticated and (probably) less energy-efficient grazing light technique must be used to avoid a harsh reflection to the viewer.

The reflection of interior lights and objects in selectively coated glazing can produce another type of glare. Designers should consider optical coatings that minimize these reflections, especially if there is a desire to “see through” windows at night.

VEILING REFLECTIONS IN COMPUTER SCREENS

The lighting industry has given much attention to the problem of avoiding veiling reflections in computer screens. This was a dramatic problem with the advent of the early black-screened monitors, where a reflection of a bright luminaire against the dark background could make large areas of information difficult or impossible to see. With the introduction of white-based screens, with flatter and diffusing glass, this problem is somewhat ameliorated, but remains an important concern. Standards for designing office space appropriate for white cathode ray tube screens are addressed in the *IESNA Lighting Handbook's* recommended practice RP-1.

The computer industry continues to advance at a rapid pace. Many current innovations are directed at developing smaller, flatter, higher resolution and lighter weight display devices to make viewing information easier under all kinds of conditions. With laptop computers came the introduction of liquid crystal display (LCD) screens, which are now spreading to standard desktop applications. Features such as easy adjustability of the angle of view, a matte surface and a flat screen make veiling reflections easier to avoid.

Computer users now also have the option of ever larger display screens and higher resolution to solve visibility problems. (A side benefit of flat screen LCD screens is that they consume much less power than conventional CRT screens, thus saving energy as well.) Speaking computers are also giving visually impaired users more access to computer technology. Simultaneously, an ever-expanding array of handheld devices is bringing numerous LCD micro-screens into the workplace, on telephones, watches, calculators and personal digital assistants (PDAs), adding another visual challenge. The technology of computer-based tasks promises to continue to evolve faster than the lighting industry can develop generalized illumination guidelines in response to these new technologies.

Figure 4-1 – LCD Screens in the Workplace

There have always been at least three ways to solve a visibility issue: enhance the illuminance conditions (with more appropriate light), enhance the vision of the viewer (with corrective lenses), or improve the visibility of the task. The computer industry itself has been the major source of innovations to resolve visibility issues and making computers as easy and trouble free as possible.

4.3.3 Lighting People and Objects

Advanced Guideline – Modeling of Faces or Objects

In human vision, shadows and highlights enhance the perception of three dimensions. Both are the products of directional light sources. The sun and the moon produce well-defined shadows, and are considered dramatic and attractive light sources.

Diffuse light, like the light from a cloudy sky, produces an even light that is relatively shadow-free. Once considered desirable, it is now realized that shadow-free light can fail to render changes in surfaces making a space or task less visible. To model a surface for better recognition of its shape and features, in general some percentage of directional light is considered important.

… blend direct and indirect lighting to provide a combination of comfort and modeling …

the direct component should be at least 20–25% of the total illumination …

As an advanced guideline, designers are encouraged to consider using a blend of direct and indirect lighting in most designs to provide a combination of comfort and modeling. The percentage of direct component will vary according to the project requirements, but to achieve a minimum of modeling, directional light for an object or area of interest should be at least 20–25% of the total illumination. Section 7.5 provides specific information about direct and indirect lighting systems.

Daylighting often provides a highly directional source of light, and excellent three-dimensional modeling

Daylighting in buildings often provides a highly directional source of light, and excellent three-dimensional modeling. The provision of a window within a space will create highlights on three-dimensional surfaces. A skylight overhead provides a very natural sparkle on the tops of objects. Since light from a window is primarily traveling in a horizontal direction, it can provide excellent facial modeling. For more about daylight as a light source, refer to section 6.3; for information about daylight systems, see section 7.4.

Shadows are particularly important in rendering three-dimensional forms in space. For instance, in designing facilities for care of the aging, shadows are essential in revealing steps and grade changes, wall edges, and other basic building elements that the younger eye has less difficulty seeing with ordinary lighting. In such cases, contrast can definitely improve visibility. (See The Aging Eye, section 2.1.6, for more about special visibility needs for the aging.)

Advanced Guideline – Surface Characteristics

Use lighting techniques that reveal texture to enhance visual perception …

In recognizing the benefit of surface revelation, the new IESNA procedure demonstrates a modern view of the role of lighting design in architecture. Once limited to special buildings and projects, lighting techniques that reveal architectural nuance like texture enhance visual perception, and have become more commonly requested by building owners and architects.

As an advanced guideline, employ light rendering programs like Radiance or Lightscape to confirm the effect of lighting designs in rendering building surfaces and other surface characteristics. This is where the power of these tools is unmatched in the profession. The ability to illustrate the revelation of texture, specularity, color and pattern is a compelling tool in studying and presenting these lighting techniques. These tools are described in section 4.4.

Advanced Guideline – Points of Interest

It has been long recognized in retail and museum lighting design that the human eye is attracted to the brightest points, and in comparison, dark areas are hardly looked at. As a primary design tool in these types of spaces, designers use highlights of up to 10 times the ambient light level to draw attention to key displays.

Less recognized but equally important, most award-winning lighting designs employ contrast and non-uniform illumination in an artful manner to achieve aesthetic purposes. Techniques range from the illumination of room surfaces or objects, as in wall-washing or cove lighting, to the use of bright sparkling elements, such as crystal chandeliers.

As an advanced lighting guideline, recognize that it's wasteful to create more lighting than is needed. Carefully select highlights, and use a minimum effective highlight level. Strategies include creating highlights in contrast to lower ambient illumination levels and creating highlights with efficient sources as close to the object or surfaces as possible. Small points of light from fiber optic sources or LEDs may offer efficient ways to create highlights or attract attention where specifically desired.

... create highlights in contrast to lower ambient illumination levels

... create highlights with efficient sources as close to the object as possible

The high levels of illumination that are easily achievable from daylighting are a very energy efficient way to provide highlights and focus attention. For example, the center of a store can be daylit with skylights, pulling customers deeper into the store, or central circulation areas can receive high illumination levels from daylight, emphasizing their central importance in the building. Such designs should carefully consider alternative nighttime illumination strategies from electric sources that do not try to duplicate the high level of illumination available from daylight.

In chapter 5, the grocery store and specialty retail store applications provide examples of the use of highlights in lighting design.

Advanced Guideline – Sparkle/Desirable Reflected Highlights

Sparkle and related reflected highlights have recently been recognized as essential elements of lighting design. These issues are often very similar to those discussed in Advanced Guideline – Points of Interest.

However, there are many commercial and industrial tasks where highlights are critical to the work. Workers often use specular highlights to judge workmanship, assess surface quality, and evaluate the quality of materials. As an advanced guideline, assess these nuances of task work and employ lighting systems that enhance, or in some cases conceal these effects. Computer modeling using Radiance or Lightscape can prove to be an exceptional tool. See section 4.4 for more about computer modeling tools.

4.4 Implementation

This section describes tools and methods for making lighting calculations (4.4.1 and 4.4.2) and evaluating the cost effectiveness of design alternatives (4.4.3).

4.4.1 Lighting Analysis Tools

Introduction

Lighting calculations have always been part of the basic practice of illuminating engineering. Calculations using a simple hand calculator (or slide rule) were once common, but the results of this type of calculation are limited to broad generalizations and averages. These days, computer calculations, requiring merely a modest personal computer and relatively low-cost software, are the standard for virtually every lighting practitioner.

This section provides an overview of lighting design analysis tools, including calculation methods and software programs. Section 4.4.2 describes design analysis tools for daylighting in more detail.

Hand Calculations

The Lumen Method

The lumen method, also known as zonal cavity calculation, is a quick and simple technique for predicting the average illuminance level in a room. The lumen method's major drawbacks are that it determines neither the range of light intensity in a room nor where differences in light intensity levels occur, and it can't provide information about lighting quality, visual performance or lighting patterns in the room. This method is especially inaccurate for non-uniform lighting systems.

The lumen method still has its place, however. It permits reasonably effective comparisons of competing general lighting systems, and it lends itself quite well to the lighting retrofit market. Because of the wealth of product data, simplicity of the formula and the ease of incorporating it into spreadsheets, the lumen method continues to play an important role in everyday lighting design. Lumen method calculations are described in more detail below.

Lumen method calculations are typically templates for spreadsheet programs or short routines built into handheld computers. Calculations have simple input requirements:

- Physical characteristics of the room, including length, width and height
- Ceiling, wall and floor reflectance (% of light reflected by the room surfaces)
- Work plane height (that is, desk height or height above the floor at which the visual work is to be performed)
- Distance from the work plane to the luminaires
- Coefficient of utilization (CU) for the luminaire: the percentage of initial lamp lumens that are delivered to the work plane. This value depends on the luminaire design and the characteristics of the space where the luminaire is located (see above bullets).
- Number of lamps per luminaire and initial lumen output of each lamp
- Light Loss Factors (LLFs): scalar multipliers that account for the degradation of rated initial lamp lumens. Light loss factors may be either recoverable due to maintenance of the lighting system and room, or non-recoverable and constant. Light loss factors include dirt accumulation on luminaires and room surfaces, lamp depreciation, ballast factors and thermal application effects.

The lumen method can be used to calculate the average illuminance incident on the work plane once the lighting system has been designed. Alternatively, the method may be used to calculate the number of luminaires required to produce a desired light level. While the method is most commonly used with direct lighting systems, it can also be used with indirect and direct-indirect lighting systems.

While the method easily lends itself to hand calculations, spreadsheets and personal handheld computers, obtaining manufacturers' data is still required. The more powerful programs require complete photometric data, but basic CU data is available on many product "cut" sheets, and generic data can often be substituted with only a modest loss of accuracy. Some spreadsheets combine the lumen method calculation with an economic analysis program, especially for evaluating lighting retrofits.

Basic Point-by-point Lighting Programs

These programs determine light levels at specific locations in a space. They can predict the brightness of room surfaces and give the patterns of light on the ceiling, walls and floor. Some programs calculate special figures of merit such as equivalent sphere illumination (ESI) and relative visual performance (RVP), metrics of lighting quality and visual performance. Other programs can address glare issues through calculation of uniform glare rating (UGR) and visual comfort probability (VCP). The sidebar, Common Lighting Performance Terms, describes these concepts in more detail.

Graphically enhanced point calculations go beyond these capabilities by providing graphic representations of the results. These may include color or gray-scale plots and isolux (isofootcandle) plots for either interior or exterior lighting, and three-dimensional perspective renderings of an interior space with its lighting system.

These programs are useful for interior electric lighting and daylighting, and can also be used for exterior lighting calculations requiring consideration of reflected light such as from canopies or walls. All modern programs run in Microsoft Windows and can obtain input space geometry from user input or from a .DXF or .DWG file.

Virtually all modern programs designed for everyday use in lighting design employ “radiosity,” a modern form of radiative-transfer calculations that have been used in point calculations since the 1970s. These programs are more precise in their calculation abilities, and thus require more detailed input, including:

- Room dimensions, work plane height, and luminaire mounting height (for pendant mounted luminaires).
- Room surface reflectance, including "inserts"—portions of room surfaces that may have different reflectance.
- Detailed luminaire photometric data in IESNA format.
- Precise location and orientation of luminaires using x, y, z coordinates, or using an interface with CAD programs.
- Light loss factors and any other multiplying factors to adjust the lamp and ballast output from the assumptions used in the luminaire photometry.

Point calculation programs calculate the lighting effects caused by specific luminaires in specific rooms. They cannot choose an appropriate lighting system given the designer's requirements. Most programs can only analyze an empty rectangular space lighted with electric lights and will provide the following output:

- Illuminance (lux or footcandles) on a horizontal work plane at selected points in the room, as well as summary statistics such as average, maximum, minimum, and standard deviation of illuminance values.
- Room surface luminance (candelas per unit surface area) or exitance (lumens per unit surface area). These results are based on the assumption that room surfaces have a matte, not shiny, finish.
- Lighting power density (watts/m^2 or watts/ft^2).

Point calculation programs may also have some or all of the following capabilities:

- Daylighting analysis. Calculated illuminance values and light patterns include daylight contributions through windows and skylights as well as contributions from the electric lighting system. Consideration of daylighting generally requires that outdoor illumination conditions be specified along with details about the orientation and transmission characteristics of the building's fenestration.
- Partition analysis. The effect on interior partitions or other light-blocking objects in the room is considered.
- Calculations and analysis taking into account furniture, partitions, and interior elements like columns and pilasters. These and other “objects in space” increase the realistic quality of renderings, but can add considerable computational time.
- Visibility and visual comfort metrics. UGR (uniform glare rating), ESI (equivalent sphere illumination), RVP (relative visual performance) and VCP (visual comfort probability) are the principal metrics computed by these programs. They are calculated for a specific location in the room and for a specific viewing direction.

Output from these programs is usually a chart of calculated values, an isolux (isofootcandle) plot, or a shaded plan with gray scales representing a range of light levels. All programs print results, and some will display the results directly on the screen. Most programs offer three-dimensional, black-and-white or color-shaded perspective views of the room showing light patterns produced on the room surfaces by the lighting system.

Modern point calculation software requires Pentium-class or greater computing power; exact requirements vary with the capabilities and design of a specific program. The run time for point calculations can range between several seconds to several hours, depending on the software and hardware used. Calculation complexities, especially rooms of unusual shape, many internal objects, or those with a large number of luminaires, increase calculation time dramatically. For instance, a simple box room with four luminaires can be completely analyzed (including daylighting) on a Pentium II class machine in about 30 seconds; adding a single desk in the middle of the room can double or triple execution time.

Programs for general use will range in cost between $100 and $900, depending on features and capabilities. Some manufacturers offer software for free or a nominal price (less than $100), but these programs are generally limited to a stripped down version of the “real” program.

Advanced Lighting Programs

Advanced programs include both radiosity and ray-tracing programs. They are capable of extreme accuracy in spaces of complex geometry. Most generate high quality, semi-photorealistic images depicting interior and exterior lighting, including daylight.

Because ray tracing is significantly more computationally intensive than radiosity, ray-tracing programs are much less common. Ray-tracing programs require considerably more computer time, data entry time, and operator expertise. However, ray-tracing programs generally produce superior visual results, often making them worth the time and expense for critical lighting designs and evaluations. Ray-tracing programs are uniquely capable of demonstrating effects and issues caused by specular surfaces, and are the only programs that render highlights such as reflections in polished surfaces or glass. Some programs combine the computational speed of radiosity with the accuracy and realism of ray tracing, permitting a practical program for common use.

Advanced radiosity programs have greater capabilities than basic programs, including:

- Analysis of rooms of any shape
- Rooms can have sloping and complex ceilings
- Realistic objects in space
- Faster execution time
- Much more realistic renderings

Advanced ray-tracing programs are the most accurate means of computing lighting effects. By tracing each "ray" of light, extremely complex visual scenes, including furniture, artwork and windows, can be analyzed exactly. Difficulty notwithstanding, ray-tracing programs display lighted rooms in full color, with accurate light patterns on room surfaces and partitions, and realistic shadows from realistic furniture. Fine details, such as the specular reflection from a window or shiny metal, enhance the sense of realism to levels unattainable with radiosity software alone. Some programs, such as Lightscape, use radiosity for most calculations, then add a ray-tracing “layer” for realism of specular reflections and highlights.

Pentium III-class computers with advanced graphics cards are generally needed to obtain satisfactory results with Windows-based programs. In general, the computer model is created in a 3-D visualization program, an arduous task requiring input details for every object and material to be rendered. The lighting program imports this data, lighting data is added, and the analysis performed. Depending on the complexity of the design and the computer power available, program run time can be minutes or even hours.

For people with access to a Unix-class graphics workstation, the public domain program Radiance is perhaps the most powerful. Specialists with high-powered graphics workstations have used Radiance to produce unprecedented real-time walkthroughs of spaces. However, the program was not originally developed for commercial use, and the learning curve is very steep, requiring a very large investment in time, computer power, and patience. A Microsoft Windows version of Radiance has recently been introduced; there is no experience data yet.

Rendering add-ins to AutoCAD and 3D Visual Studio/3D Viz are also available. Rendering add-ins are a relatively new phenomenon, as they take advantage of lighting algorithms to illustrate games and architectural programs with considerable realism. However, because most of these programs are illustrator's tools and not necessarily professional lighting programs, it is probably a good idea to determine the accuracy and features of the program with respect to lighting and daylighting.

Specialty Calculations

There are several lighting calculations that are best performed using a program specifically designed for them. In particular:

- Most exterior lighting calculations don't require calculations involving reflecting surfaces such as ceilings and walls, so faster, simpler programs have been written for this task.
- The unique nature of theatrical and performance lighting equipment is best served by an application-specific user interface, although the calculations may be very similar otherwise.
- Easy-to-use programs and templates have been developed as aids for common lighting problems, including skylight design (see section 4.4.2) and display lighting design.

Exterior Lighting Calculations

Exterior lighting programs are used for parking lots, roadways, pedestrian paths, and special situations such as airport aprons, car sales lots and sports fields. Exterior lighting calculations are very similar to interior calculations, except that they are simpler, since no light reflectance from room surfaces are calculated. Exterior programs generally allow the user to aim the luminaire (interior programs usually assume the luminaire will be parallel to the floor). Input data typically include the following:

- Plan dimensions of the site to be studied, usually entered in x, y coordinates or through a CAD interface
- Points on the site where illuminance is to be calculated. Some programs permit blocking out the printing of light levels on areas of the site where light levels are not critical, or where buildings or trees would block the light.
- Luminaire photometry
- Mounting heights, site locations, orientations, and tilt of luminaires
- Lumen output of the specified lamp
- Light loss factors due to lamp aging, ballast factor, and luminaire dirt accumulation

As with interior programs, photometric data files for exterior luminaires are generally supplied by manufacturers on data disks in IESNA format. Or, if a data disk is not available, the candlepower data may be keyed in by hand from the manufacturer's photometric report.

The most common form of exterior lighting analysis is the calculation of illuminance on horizontal and vertical planes. Horizontal planes usually are used for roadways, pathways and parking lots, while vertical planes are typically used for parking lots, sports fields and automobile display areas. Exterior lighting programs are also very useful in calculating light trespass onto adjacent properties, the lighting of adjacent building facades, and evaluating a lighting system for the use of exterior closed circuit television cameras. Advanced tools including the calculation of veiling luminance are available when using some programs.

Because the results of roadway and parking lot calculations lend themselves well to graphic presentation, output from most of these programs is provided as a grid of illuminance levels, gray-scale tones, and/or isolux (isofootcandle) plots. Most programs will limit analysis to areas of the site where illumination is important, such as between the curb lines in roadway analysis. No analysis is performed (or at least not printed) for areas of the site where light levels are not critical. Many programs can take into account the shadowing from buildings. Most exterior lighting programs are designed to run on Windows-based computers.

Many exterior lighting programs are designed to work with CAD programs. CAD interface capabilities allow rapid data input and layout using a mouse or digitizer. This type of drawing and computing relationship accelerates and improves the accuracy of site and roadway lighting design. Locations of luminaires can be determined from CAD data, and output information such as isolux/isofootcandle plots can be entered directly onto the base civil engineering or site plan. Enhanced screen and printer images include three-dimensional representations, such as perspective-isolux drawings.

Exterior programs for general use cost $200 to $1500. Several outdoor luminaire manufacturers will supply software to specifiers for a nominal fee ($0–$100), but these programs may only analyze that particular manufacturer's luminaires. For most commercially available lighting software, a reasonably current office computer is generally all that is needed.

General Purpose Energy Simulation Programs

Energy simulation programs such as DOE-2, BLAST and EnergyPlus are not really lighting programs, but they do simulate the energy used by lighting systems and are useful in evaluating the interactions between lighting system improvements and HVAC systems. The programs enable one or more lighting systems to be modeled in each space. The peak power is defined for each system and an operation schedule is assigned. The operation schedule indicates the percent of the lights that are operating for each hour of the year. Most of the programs can do basic daylighting calculations for a single lighting reference point.

Application Guidelines

Approaches to Lighting Design

Lighting design strategy often determines the appropriate type of lighting calculation. Two design approaches are discussed here: general lighting approaches and task-ambient lighting approaches.

General Lighting

The general lighting design approach is a common strategy used to provide a fairly uniform amount of light throughout a room. If the task location in a room is likely to vary widely, or if the space is likely to be frequently reconfigured to accommodate changes in work groups (such as adding staff and moving workstations around a couple of times per year), then it may be advisable to design for task levels of illuminance everywhere in the room.

The general lighting system is usually a regular pattern of luminaires that produces very even light levels, slightly higher than the average value in the center of the room, and slightly lower in the outer corners of the room. Lumen method calculations are appropriate for the design of general lighting systems.

Multicomponent Lighting Design

Task-ambient lighting and other multicomponent design approaches tend to be non-uniform, with lower ambient light levels surrounding brighter task areas. For example, in a task-ambient design, luminaires might be concentrated primarily over work areas, while an indirect lighting system provides relatively low levels of general (ambient) illuminance. This design strategy usually requires point calculations to ensure that luminaires are correctly located to produce the lighting level and quality necessary for performing visual tasks at the needed locations.

The skilled application of computerized point lighting calculations can optimize lighting levels in both the task and ambient domains in order to minimize energy consumption. The lighting professional should consider the use of point lighting calculations, both to design more energy-efficient spaces, and to create spaces with more drama and visual interest.

Point calculations are an exceptionally accurate way to compare general lighting systems. While the easier lumen method allows the comparison of average illuminance, point calculations permit the comparison of uniformity of light on the work plane, the patterns of light produced on ceilings and walls, and task contrast rendering. More specifically, point calculations allow consideration of the effects listed below.

- *Effects on Room Surfaces.* By evaluating the patterns of light on a wall caused by a row of compact fluorescent downlights, an aesthetic evaluation can be made. Artwork locations may be selected or lighting may be designed to highlight artwork. It may also be possible to determine whether the pattern created on a wall will produce luminance extremes that will cause glare or reflections in VDT screens.
- *Indirect Lighting Effects on Ceiling.* When they are too close to the ceiling, indirect lighting systems may create definite stripes or pools of light on the ceiling that are distracting and that may image in VDT screens. Careful ceiling luminance calculations can help identify the problem, and allow comparison of lighting products with various optical distributions and suspension lengths to reduce the effect. Gray-scale printouts or shaded VDT screen output of luminance make visual assessments possible.
- *Interior Task-Ambient Lighting.* Point calculations should be used for any type of lighting design where the task locations and types are well known and are unlikely to move without a lighting redesign. They may also be used for lighting designs where tasks that move end up in predefined locations.

Cautions for Point Calculations

In the case where a task light is used, or where an indirect luminaire is mounted within 12 in. of the ceiling, point calculations aren't always appropriate. In general, if the luminaire is close to the surface where lighting patterns are to be evaluated, a *near-field* situation exists. A shortcoming of the mathematics used in point calculations is that these near-field calculations are comparatively inaccurate unless near-field photometric data is available from the luminaire manufacturer, or the computer program is capable of adjusting the luminaires' characteristics to improve the accuracy of the results. Otherwise, it may be more accurate to evaluate the light patterns from the task light or indirect luminaire empirically.

Common Lighting Performance Terms

Luminous Flux, measured in lumens, refers to the gross amount of light generated by a source, irrespective of the intensity of the light in a given direction.

Candlepower is the measure of the intensity of a light source in a given direction, measured in candelas (cd). Candlepower distribution curves describe the direction and intensity of light radiation by a luminaire or a light source.

Illuminance describes the amount of light falling on a surface. If the surface is horizontal, light striking it is known as horizontal illuminance; if the surface is vertical, it is called vertical illuminance. The average illuminance on a surface may be calculated by dividing the number of lumens falling on the surface by the area of the surface. Or, the illuminance incident at a point may be calculated as the candlepower of the light ray from the light source to the point, divided by the square of the linear distance between them, times the cosine of the angle between the light ray and the normal to the surface. Both methods result in "footcandles" if the area or distance is measured in square feet, or in "lux" if the area or distance is measured in square meters (1 fc =10.16 lx). Illuminance can be measured with an inexpensive meter. This value is still used as a measure of lighting quantity and as a standards value.

Equivalent Sphere Illuminance (ESI) is a measure of how visible a specific target is under a proposed lighting system, as compared to the same target illuminated by a uniformly bright hemisphere, expressed as the illuminance created by the hemisphere. ESI can be a powerful design tool in evaluating performance of competing lighting systems. In simple terms, ESI indicates how much illuminance on the task actually aids visibility, as opposed to causing veiling glare. This metric is very difficult to measure in the field or calculate by hand; however, available computer programs are able to compute it easily and can be an aid to understanding basic principles of lighting quality.

Relative Visual Performance (RVP). Based on experimental measurements made at the National Research Council of Canada, this is a metric describing the potential of performing a visual task accurately under a very specific set of conditions. RVP is an important tool for comparing lighting systems. It is expressed as a percentage that predicts the probability of successfully performing a task where speed and accuracy are important by measuring how well the lighting system renders the target's contrast. User age, precise reflectance characteristics of the task, distribution of the light approaching the task, viewing location, and orientation with respect to the task and lighting system must be known to compute RVP at a point. This does not diminish its utility when comparing lighting systems. RVP for an existing task, user, and lighting system may be determined using an instrument designed for this purpose. RVP is considered an important tool for comparing lighting systems, but it has been slow to gain widespread acceptance, because it is generally limited to those who comprehend how it is calculated and understand its limitations and narrow application.

Visual Comfort Probability (VCP) is a calculation taking into account the relative brightness of a lighting system from a given viewing angle, resulting in the likelihood (as a percent) that a lighting system will be visually comfortable. VCP data were confirmed experimentally using uniform layouts of lensed fluorescent luminaires. While it is typical practice to extrapolate the VCP concept to apply it to various size louvers and luminous ceilings, it should be noted that VCP data have not been experimentally confirmed using these systems. As such, one should be cautious in using VCP to evaluate the potential visual comfort of lighting systems using other than lensed luminaires.

Exitance, Luminance, and Brightness are properties describing how light is reflected from or transmitted through a real (or imaginary) surface. **Exitance** is the total quantity of light emitted by, reflected from, and transmitted through a surface into a complete hemisphere. It is expressed in units of lumens per unit surface area. **Luminance** is a very important concept in lighting, since luminance is what we actually see. Rigorously, luminance is defined to be the ratio of the intensity of light produced by a surface in a given direction to the projected area of the emitting surface. In SI units, luminance is generally expressed as candelas/meter^2. In English units, luminance should generally be expressed in candelas/ft^2. The foot-lambert unit for luminance that has been used in the past has been deprecated and should be avoided. **Brightness** is used to describe the strength of the physical sensation caused by viewing surfaces (or volumes). Brightness is related to luminance, but takes account of the fact that a surface with a luminance of, for instance, 100 cd/m^2 will not appear twice as bright as a surface of 50 cd/m^2.

Spacing to Mounting Height Ratios and **Spacing Criterion** (S/MH and SC) refer to the maximum recommended spacing between luminaires to achieve uniform general lighting. S/MH is often expressed as "parallel" or "perpendicular," and refers to the ratio of the center-to-center distance between luminaires to their mounting height above the work plane in the direction either parallel or perpendicular to the length of the lamps. Current luminaire photometry uses the term "spacing criterion" (SC) instead. While these metrics are useful for lumen method general lighting calculations, neither S/MH nor SC is applicable in spaces with workstation partitions or where task-ambient design is appropriate. Spacing criterion is described further in section 7.3.2.

Resources

Each year, the Illuminating Engineering Society of North America (IESNA) publishes a lighting software survey in *Lighting Design + Application.* Products are surveyed in many areas, including hardware requirements, analysis features, applications, types of output, user features, and price. At the time of the printing of the *Advanced Lighting Guidelines,* the IESNA survey was the most up to date and complete source of information on lighting software on the market. The following are some of the more readily available and recognized software available at the time of this document's development.

Table 4-3 – Lighting Software Programs

Category	Program	Manufacturer	Description
General Purpose Programs and AutoCAD Extensions	CALCU-LITE 5	The ScreenMaker Williamstown, NJ	Basic lighting program
	AGI	Lighting Analysts, Inc. Littleton, CO	Advanced radiosity lighting program with rendering
	LUMINAIRE GLOBAL ILLUMINATION TOOLS	Jissai Graphics	Radiosity add-in to 3D Viz with rendering
	LUMEN-MICRO 2000	Lighting Technologies, Inc. Boulder, CO	Advanced radiosity lighting program with rendering; also, Simply Lighting basic lighting programs
	LITE-PRO	Columbia Prescolite Spokane, WA	Radiosity lighting program with rendering
	LUXICON	Cooper Lighting Peachtree City, GA	Radiosity lighting program
	VISUAL	Lithonia Lighting Group Conyers, GA	Advanced radiosity lighting program
Radiosity and Ray Tracing Program	LIGHTSCAPE 3.2	Autodesk San Rafael, CA	Combines radiosity with ray tracing for rendering accuracy
Ray-tracing Program	RADIANCE (Unix) and Desktop RADIANCE (Windows— AutoCAD 14)	Lawrence Berkeley National Laboratory University of California, Berkeley, CA	Ray-tracing program that is computationally intensive but produces the most realistic renderings

Note: These listings are not exhaustive and do not imply applicability or endorsement. Additional programs are available. Refer to the annual lighting software survey in *Lighting Design + Application* magazine and http://www.lightsearch.com for additional sources of software and comparative analyses.

4.4.2 Daylighting Design Analysis Tools

Unlike electric luminaires, daylight apertures are not routinely tested for their photometric performance. The evaluation of an advanced daylight luminaire usually involves one or more of the following specialized analysis tools.

Manual Calculations

Several methods have been developed for manual calculation of interior daylight levels. Most notable among these are the lumen method of toplighting and sidelighting and the Lune Method (see *IESNA Lighting Handbook*). Because of the dynamic nature and complexity of daylight and the plethora of potential apertures, these techniques are quite time consuming and provide only a rough estimate of performance. They have substantially been replaced by scale model and computer simulation techniques.

Scale Models

When constructed appropriately, a daylighting scale model provides accurate qualitative and quantitative evaluations of daylight performance. Scale models (from 1/8 in. = 1 ft to over 2 in = 1 ft) furnish information about shading patterns, direct sun penetration, daylight distribution and glare conditions. Smaller models are used for site analysis; larger models, for evaluation of interior spaces. Models must be light tight and constructed with appropriate dimensions and surface reflectance. Larger models may use actual building components (glazing, surface treatments, etc.) to improve accuracy of the model.

Scale models are relatively easy and inexpensive to construct, but testing is time consuming and may require access to an artificial sun and sky facility (known as a heliodon) for accurate studies of multiple scenarios. These facilities are available at some university and utility laboratories. Model studies are conducted for both direct sun and overcast sky conditions. Light level measurements are recorded with small photosensors placed in the model or documented with photographs or videos.

If well built, the quantitative accuracy of scale models can be higher than most current computer simulations. The Lighting Design Lab in Seattle, Washington, has developed a training video on the construction and testing of models in an artificial sun and sky.

The ultimate model study is a full-scale mock-up of the space. Though expensive, these studies can give the most accurate qualitative and quantitative information about the daylight and electric light and allow the designers and clients to experience being in the space. They are usually only constructed for a small representative portion of a larger extended building. Some utility-funded lighting facilities have large spaces with movable ceilings and window walls which may be used to construct the interior of a full scale space.

(a) scale model (b) Lightscape computer simulation (c) full-scale mock-up of classroom

Figure 4-2 – North Clackamas High School Classroom Study Tools
Photographs of North Clackamas High School, Portland, Oregon, courtesy BOORA and LDL.

Computer Simulations

An increasing number of computer programs are available to simulate quantitative daylight levels and qualitative renderings of architectural space. The programs vary in their ability to represent complex architectural spaces (sloped and curved walls, for example) and handle specular reflections. The most sophisticated programs take architectural information from the designer's CAD file, add detail, and generate rendered, textured, color images with specular reflections for a particular location, day and time. They can include the effect of both the daylight and electric light in the space and can generate an automated "walkthrough" of the space for a particular day and time.

The quantitative accuracy of these programs is inherently constrained by the current lack of photometric data for glazing and fenestration products and the dynamic range to qualitatively represent glare conditions. However, use of the daylighting analysis features of either radiosity or ray-tracing programs can be extremely useful, if not perfectly accurate. Simulations for simple spaces that don't require a refined rendering can be accomplished quickly (frequently faster than scale models) and with quite reasonable accuracy. More refined simulations require technical expertise and extensive modeling time. This time is abbreviated if the designer has already constructed an appropriate CAD file. Repetitive parametric runs are easily accomplished.

Daylighting Control Simulation Tools

Some of the common daylight control simulation programs used in the United States are listed in Table 4-4. A more comprehensive list can be found in Daylighting Performance & Design (Ander 1997). None of these tools includes the ability to evaluate savings due to lumen maintenance strategies, lengthening of relamping schedules, and any productivity improvements that may result from the daylight and increased flexibility of the controls. These will need to be calculated separately.

Table 4-4 – Daylighting Control System Simulation Tools

Program Tool	Description	Cost and Availability
DOE-2	Hourly building energy simulation tool developed by LBNL. Commercially available from a variety of suppliers Models both windows and skylights. Evaluates impact on HVAC and savings from lighting controls.	Cost: $400–$1,400 Availability: For a list of commercial versions, go to http://gundog.lbl.gov/dirsoft/d2vendors.html
Energy 10	Hourly building energy simulation tool developed jointly by NREL and PSIC. Limited to buildings less than 10,000 ft². Models both windows and skylights. Evaluates impact on HVAC and savings from lighting controls.	Cost: $250 Availability: Contact Passive Solar Industries Council (PSIC) at (202) 628-7400 X210 or online at http://www.nrel.gov/buildings/energy10
Adeline	Electric and daylight design tool linking a selection of lighting (Superlite and Radiance) and energy software tools with a CAD program to evaluate the HVAC and lighting performance of windows and skylights.	Cost: $450 Availability: Order online at http://radsite.lbl.gov/adeline or contact LBNL Building Technologies Program
SkyCalc	Microsoft Excel-based spreadsheet program (originally derived from DOE-2 runs) that predicts lighting and energy outcomes of a given skylighting system over a range of skylight-to-floor ratios. Includes estimates of energy impacts due to lighting, heating, cooling and controls. Skylights only.	Free Availability: Download free online at http://www.energydesignresources.com or http://www.h-m-g.com

4.4.3 Economic Analysis of Lighting Systems

Some advanced lighting systems increase construction costs. Designers need to know when these additional costs can be justified through future energy savings or other benefits. As discussed in section 2.3, many of the benefits of efficient lighting systems—such as productivity gains—are difficult to quantify. Environmental impacts are also elusive and are often called externalities because they are external to most analyses of economic performance.

The construction or initial costs of lighting systems are a key concern to all players. To be successful, an advanced lighting system must also meet the economic criteria of the building owner. These criteria may not appear immediately rational to the outside observer, as discussed in Economic Limitations below. Comparison of alternative lighting systems should include all relevant costs associated with a lighting system, and use an appropriate analysis tool, as discussed in Economic Decision-Making below. Lighting retrofit projects should start with a screening of all possible projects for those that have the greatest potential, a quick scoping study, and then if warranted, an investment grade audit should be performed, as described below in Retrofit Assessment and Lighting Audits.

Economic Limitations

Energy efficiency advocates have long thought that if only they could prove the economic rationality of efficiency improvements, then surely reasonable decision-makers would choose the more efficient strategies. This has repeatedly proved a much more difficult sell than originally thought. Lighting systems in commercial buildings have been greatly undervalued and often are of much poorer quality than could be easily justified economically. Reasons for underinvestment in lighting systems include:

- Last-minute changes to the lighting specifications that allow the substitution of inferior products.
- Decision-making based on initial installation costs, rather than long-term operating costs.
- A market culture that is driven by the sense that "what everyone else is doing" must be right.

- A deep-seated belief that lighting doesn't really affect worker performance (see the sidebar **There's No Such Thing as the Hawthorne Effect** in chapter 2.)

Substitutions

Lighting installations in commercial buildings often suffer by being the last major system to be installed in a building, and are perhaps therefore the most susceptible to last-minute cuts to the construction budget. Lighting designers complain that their designs are frequently changed without their review by a "value engineering" process where contractors recommend that specified items be replaced with lower quality products. Construction scheduling is also often used to "break the spec" by claiming that the specified product is not readily available and that waiting for it will slow down construction. Building owners who called for high quality lighting during the design process may discover after occupancy that they received only mediocre lighting systems as a result of decisions made during construction.

Importance of Initial Costs

Like it or not, initial cost is the prime criterion for evaluating most construction decisions. Construction budgets are extremely sensitive to a system's first cost, and are much less sensitive to a system's life-cycle costs. Construction and renovation projects are seen as one-time expenses with pre-set budgets, managed independently from other business expenses. Design teams are tasked with meeting the budget as their primary objective. Furthermore, most private sector companies must borrow money for building projects. With financing, the time value of money puts even more pressure to keep the construction budget as low as possible. Businesses must prove to the bank that their building is worth the investment. Prudent risk management generally suggests keeping that investment as low as possible, putting even more pressure on keeping the construction budget as low as possible.

Government agencies have tried to change this "initial cost" culture by insisting that all public building projects be evaluated using life-cycle cost criterion. Clear rules and procedures have been developed, evaluations are dutifully performed and recommendations made. However, even in these situations, the construction budget and schedule often become the final criterion in decision making. Recommendations can be ignored, but budgets must be met. Thus there is enormous pressure to reduce the initial cost of lighting systems. Any increase in cost must be convincingly justified; and even then, it's likely to be ignored when the project team is confronted with the final budget.

Market Culture

It's also important to understand the "market culture" involved in lighting decisions. Both developers and government agencies often want to be doing what everyone else is doing; they don't necessarily want their buildings to be exceptional. Once a particular lighting system is accepted as "standard practice" or as "modern," many people assume that it's "better" and use the system indiscriminately in every application. A recent example of this mentality is the pervasive use of parabolic luminaires whether they are needed for glare cutoff or not. This market culture is not economically rational, but it can be influenced by leaders in the field who make thoughtful decisions.

The key to greater investment in lighting systems will ultimately depend on a widespread understanding that quality lighting makes an important contribution to worker performance. Efforts are underway to quantify these benefits, as discussed in section 2.3 – Light and Productivity.

Economic Decision-Making

Most companies spend very little time assessing the economic value of lighting alternatives. The easiest path is to do "the same thing we did last time." Some companies may do a quick payback check, which may be no more than a "back of the envelope" calculation. However, without more careful financial assessment, many of the advantages of advanced lighting systems will be ignored or undervalued.

There are a variety of methods to evaluate costs and benefits of lighting alternatives and put them into an economic equation. These include:

- Simple payback, which compares installation costs to the expected first-year savings from the new system, usually just energy savings. It's expressed as the amount of time required to pay for the incremental cost of the system with increased savings, in terms of months or years. Simple payback always underestimates the value of energy and maintenance savings because it doesn't consider the time value of money.
- Life-cycle cost analysis (LCA), which considers all the costs over the life of a system, including energy, maintenance, disposal, and the time value of money based on expected inflation rates or standard interest rates. It's very useful when comparing systems with different life span and period costs, like maintenance, that occur on different schedules. Different systems are compared by their annualized cost of ownership.
- Return on investment (ROI), which can consider as many or as few factors as the analyst wishes. The final answer is expressed in terms of the value of the investment in the system, compared to the value of any other investment.

Publications are available that thoroughly detail how to perform these economic analyses.[1] There is a basic trade-off between simplicity and accuracy in choosing which method to use. Software tools have made the more sophisticated economic analysis methods within reach of anyone with a computer. The Federal Energy Management Program (FEMP) has developed a series of software tools to facilitate life-cycle cost analysis of energy related projects.[2] Many private-sector lighting programs also include a variety of financial analysis options.

The key to any economic analysis will always be the accuracy and completeness of the information inputs. Simple analysis based on rough guesses or defaults provide "ballpark" estimates. This level of analysis is usually appropriate at the initial states of a project. Sophisticated analysis considers more detailed data from documented and updated sources. Such careful analysis is highly appropriate to any major investment or policy-level decision.

All of the costs and benefits associated with a lighting project should be considered in a careful economic evaluation of a lighting system. These include:

- Installation costs
- Financing costs
- Design and management costs
- Energy costs
- Maintenance costs
- Human factors
- Environmental benefits (externalities)

These costs and benefits are described below.

Installation Costs

Installation costs, also called first costs or initial costs, are all the costs to purchase and install a fully functioning system in a building. They properly include:

- *Equipment cost*, including distributor's and contractor's mark-up, and shipping charges

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1 See the lighting economic analysis information included in the *IESNA Lighting Handbook, 9th Edition*, EPRI's *Lighting Fundamentals Handbook*, and various publications and software available from the Federal Energy Management Program's Web site, http://www.eren.doe.gov/femp/ordermaterials.html.

2 For more information on federal economic analysis tools, go to http://www.eren.doe.gov/femp/techassist/softwaretools/softwaretools.html.

- *Labor to install equipment*, including placement, wiring, cleaning and contractors' mark-up
- *Labor to commission* and train building employees in proper operation of the system
- *Any discounts*, rebates, or incentive payments

There are often trade-offs between equipment and labor. Reduction in wiring and installation costs can often counterbalance more expensive equipment. For example, linear pendant luminaires can sometimes reduce costs over recessed troffer alternatives by reducing the number and complexity of wiring connections between luminaires.

Similarly, any project involving moving parts or adjustable settings needs to be commissioned on-site to be sure that it is functioning as intended. Commissioning costs should be included in any budget allowance. A construction budget should also include an allowance for the contractor to train building employees in the proper maintenance and operation of systems.

Any discounts, rebates or incentive payments should also be factored into installation costs. Utility companies have often tried to encourage the installation of more efficient systems by helping to "buy down" the installation cost with incentive payments or rebates to the building owner. These programs change, so check current program rules and availability with your local utility representative rather than assuming that such incentives will be available for a given project.

Financing and Appraised Value

As discussed above, the cost of financing construction projects is considerable and becomes a motivator to keep the project "on time and on budget." Any increase in initial cost or extension of the construction finance period multiplies the final cost of a project. Depending on the specific terms, financing costs can easily equal or exceed the installation costs of a project.

Whenever possible for private-sector projects, managers should try to take advantage of the reduced operation costs and improvement in overall building value of a new lighting installation to help leverage the financing limits for a project. Banks typically determine their financing allowance based on expected income from tenants less all operating costs, times a capitalization rate. For example, with a 10% capitalization rate, which is fairly typical in the construction industry, a $0.20/ft² reduction in yearly energy costs translates into an increased total building value of $2.00/ft², which would likely cover the additional costs for a state-of-the-art lighting system.

Similarly, many people are looking for ways to help appraisers recognize the value of such energy savings when they assess the value of a commercial building for resale. If appraisers assigned an increase in value to a building with improved energy efficiency or enhanced lighting quality, it would provide a major incentive for developers to invest in those features since it would add to the building's permanent valuation. Essential to achieving this goal is an objective measure of building performance that appraisers can easily reference and compare to an industry standard. Since appraisers only compare projects within small geographic areas, typically on the scale of a city or even neighborhoods, this information must be available at a similar geographic level. One effort in this direction is the Energy Star Building program initiated by the U.S. Environmental Protection Agency (EPA).[1] Another is an ongoing project in California to develop a statewide database of building characteristics that might be used to establish industry norms by building type and age. Developed by investor-owned California utilities, this database currently resides at the California Energy Commission.

Many large institutions and governments have a difficult time financing lighting renovations, even when the financial analysis clearly shows that it would be a wise investment. To help these organizations, a new industry has evolved that essentially finances projects by taking a share of the energy savings. This approach is often referred to as "energy cost sharing," and companies that provide this service as "energy savings companies" (ESCOs). The federal government has created a new form of contracting called

[1] For more information, go to http://www.energystar.gov.

"energy services performance contracting" (ESPC) to enable federal agencies to take advantage of this financing mode.[1]

Design and Management Costs

Many analysts forget to include the cost of design services and time spent managing a project in their calculations of cost effectiveness. People often make subconscious choices here, deciding to go with a "quick and dirty" approach that can get a job done quickly, but may not optimize its quality and cost effectiveness.

Professional design services do add to a project's real cost, as does the time to manage those design services. However, an experienced and qualified practitioner knows how to optimize a lighting system for the owner's needs and can greatly improve the economic value of a project. National Council on the Qualifications of the Lighting Professions (NCQLP) requires that practitioners who have earned the designation LC (Lighting Certified) have knowledge of economic analysis and can perform this function for their clients (see section 3.3.4).

Lighting design practitioners who are asked to perform careful economic analyses or create alternative scenarios for comparison will expect to be paid for additional services. A number of utility programs recognize this increased cost and help to reimburse the designers for these services.[2]

Managing a lighting project also involves time on the building owner's end. Building owners generally prefer making quick, well-informed decisions rather than spending a great deal of time considering alternatives and approving design changes. Thus, simple proven design strategies have a decided economic advantage. Participating in special programs, such as government certification programs or utility incentive programs, can also involve considerable administrative time, especially if eligibility must be certified with much paperwork or with on-site audits. Program designers must be sensitive to this issue, or they will find the "transaction costs" will discourage participants from joining the program.

Energy Costs

A full assessment of energy costs should include:

- Per-unit energy charges
- Demand charges
- Fixed charges
- Escalation rates
- Discounts and other benefits

These factors are discussed below.

Per-unit Energy Charges. Calculating energy costs used to be relatively straightforward once you knew total wattage and hours of operation of a lighting system. Most lighting energy analysis assumed an average cost per kilowatt hour[3] and used the simple equation:

Energy cost per year = Connected load in kilowatts x Hours of operation per year x $/kWh

Equation 4-1

Per-unit energy charges become more complex when they vary by time of use. For example, some utilities charge more for electricity used during the day than at night. The average cost per kilowatt hour

[1] For more information on financing options for federal projects, go to http://www.eren.doe.gov/femp/financealt.html.

[2] For example, in California, the statewide *Savings by Design* program offers payment to design teams, as does the *Design 2000* program from National Grid serving areas of New England.

[3] *Energy User News* publishes average costs of electricity by sector and utility.

can still be calculated based on total energy bills for one year divided by total energy use for the same period. However, a better understanding of the cost savings due to an energy efficiency measure will involve knowing the time of use for different systems and the load profile for the building. (See discussion of lighting load profiles in section 3.1.4.)

Demand Charges. A more sophisticated analysis also looks at peak demand and associated demand charges. In some regions of the country, peak demand charges can become more costly than overall per unit energy charges. By reducing connected load with lower power densities, or peak demand with controls that reduce use during peak periods, building owners might save more money than the value of the straight energy savings.

Considering demand impacts makes the equation much more complex, because now you must know when particular watts are used, by season or time of day, and even how lighting loads relate to other loads in the building. Does peak lighting use coincide with peak periods defined by the utility? And do those lighting peak loads also coincide with other peak loads in the building? Such an analysis requires not only more information, but also a program that can simulate building energy use hour by hour.

Demand savings are also rarely certain, and difficult to attribute to one building system over another. Some utilities shift demand periods by weather conditions, and most buildings have different peak demands as weather changes. Some lighting strategies, like using photocontrols in conjunction with daylighting, offer considerable opportunities to reduce peak lighting demand. However, this isn't a certainty, since in any given year a utility peak load might occur during a day or time period that was not optimum for daylighting. If the building owner can't be guaranteed that demand savings are absolutely predictable, he or she may not be willing to include demand savings in a comparison between systems. (See discussion of demand management in section 8.1.5.)

Fixed Charges. Energy pricing structures seem to be headed in the same direction as telephone bills: numerous types of fees and charges, such as breaking energy charges down into connection charges, fixed monthly charges, variable time-of-day rates, and peak use surcharges. Telephone companies have learned to compete based on minimizing the advertised cost of a call per minute, while making their profit on other fees and charges. Similarly, when utility companies shift more of the cost of providing electricity to fixed charges per customer, the incremental value of energy savings to the customer is generally diminished.

Escalation Rates. If energy prices are expected to rise in the future, the value of current energy savings also increases. Of course, no one really knows what's going to happen in the future, so any guess might be as good as another, unless one is trying to compare cost-benefit analyses of projects generated under different assumptions. To simplify and standardize life-cycle cost analysis, the Energy Information Administration[1] studies energy availability and cost escalation rates and publishes an official prediction for energy escalation rates by fuels type and region. With deregulation, these predictions have become less certain.

Discounts and Other Benefits. Deregulation promises building owners even more options in fee structures. One utility might offer free phone service based on your energy bills. Another utility might offer an initial discount on energy rates for the first year if you sign on with them for multiple facility locations or across state lines. How will building owners compare lighting alternatives with this proliferation of pricing structures? If deregulation also allows the price of energy to float with the open market, much as variable rate home mortgages do, the time value of energy savings will become even more unpredictable.

Given this growing complexity, building managers will need to carefully analyze their billing structure in order to understand the relationship between energy use and energy cost. Complexity and unpredictability work against easy analysis of energy costs.

Maintenance Costs

The cost of maintaining a lighting system include:

[1] See http://www.eia.doe.gov.

- Routine maintenance, such as cleaning luminaires, troubleshooting systems, and spot replacement of early failures, including both labor and equipment costs
- Scheduled group replacement, including both labor and equipment costs
- Stocking costs to warehouse parts, or order as needed
- Disposal costs for lamps and ballasts

Labor costs of lighting systems are not trivial and should be included in any comparison between system options. Because maintenance costs are periodic, and both labor and equipment costs are likely to escalate over time, a life-cycle cost analysis is the most sensitive approach to evaluating the impacts of maintenance costs. Generally, lighting maintenance costs will be reduced by: reducing the number of luminaires and variety of components per facility; extending the system's life; improving the system's reliability; increasing the accessibility and simplicity of the system; improving the cleanliness or airtightness of a system so that there's less dirt accumulation; and making the system more environmentally benign so that disposal and liability costs are reduced. Chapter 7 provides information about lighting system maintenance issues.

Productivity Benefits

The ideal economic analysis would include human factors in the costs and benefits of different lighting systems. This is, of course, very difficult to do as it usually involves comparing apples to oranges. For example, a recent study showed that increased daylighting in elementary schools improved student learning rates by 20% on standardized math tests and 26% on reading (Heschong Mahone Group 1999). While this is clearly important to the central mission of a school district, how much is it worth in terms of an investment in a daylighting system?

It's clear that the cost of providing and operating lighting systems is minuscule compared to the cost of employees. A careful study looking only at the federal government's office workforce concluded that the yearly cost of labor, in 1995 dollars, is about $164/ft² of building area (Harris et al. 1998). This is a function of both the cost of labor and the density of the workers in the building. Many higher paid and higher density corporate offices have been estimated at $300 to $400/ft². Compare this to the cost of a new efficient lighting system, at a one-time installation cost of perhaps $2.50/ft², and the value of energy to operate it, at perhaps $.20/ft² per year.

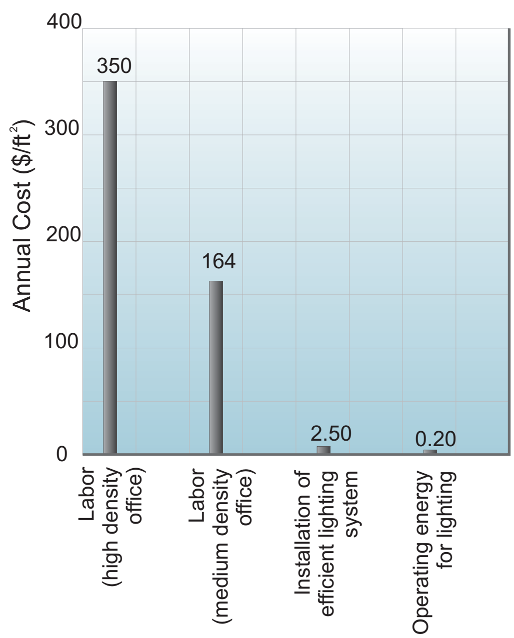


Figure 4-3 – Building Costs Relative to Business Operating Costs

In the case of the federal office workers, consider a higher quality lighting system, which resulted in a 50% increase in lighting installation cost, from $2.50/ft² to $3.75/ft². If this system also resulted in a mere a 1% increase in productivity, the additional cost would be paid for in nine months, without accounting for any other savings from energy or maintenance. For the corporate case, this payback is reduced to four or five months.

Clearly, productivity impacts are vastly more important than energy savings. A 1% increase in office worker productivity is equivalent to an additional 5 minutes of productive work per day, clearly within the range of plausibility. Actual studies have shown significantly higher productivity impacts than 1%. Researchers at Natural Resources Canada (Veitch and Newsham 1998) found that lighting conditions could be shown to affect clerical workers' performance on various tasks. Overall, these effects ranged from 1% to 25% for various task types.

This argument, however, has two sides. If a lighting system causes any loss in productivity, the impacts are just a great, but in the opposite direction. This is an excellent argument for investing in professional design services to ensure that lighting installations truly optimize conditions for workers.

Environmental Impacts

Environmental impacts that are not charged directly to a building owner are also very difficult to include in an economic analysis. While most business owners may have good intentions to help the environment, these intentions are likely to be dropped unless they can be included in the bottom-line equation. Environmental labeling programs attempt to make environmental benefits more tangible by providing a business owner with a third-party evaluation that they have achieved a real reduction in environmental impacts. Labeling programs also offer an opportunity for marketing and advertising benefits that may improve the bottom line. The U.S. EPA's Energy Star Buildings program, the U.S. Green Building Council's LEED labeling system, and various other "green" or "sustainable" building rating programs are all efforts to increase the value of environmentally sensitive buildings. An alternative approach adopted by some government agencies is a policy allowing a blanket "environmental multiplier," on the order of 10%, to the annual value of any energy savings to account for various externalities like a reduction in acid rain or smog generation due to power plants. (See section 3.2 for more information about the environmental impacts of lighting.)

Retrofit Assessment and Lighting Audits

Retrofit projects typically involve a different type of analysis than new construction projects because they compare existing conditions and costs with proposed retrofit design options. This analysis usually includes a lighting audit, an assessment of what is already in place and what the current ownership costs are. The following discusses economic analysis of retrofit opportunities; see section 7.9 for information about design criteria for lighting retrofits.

Lighting audits can be expensive, so to reduce initial costs it's wise to take a stepped approach to assessing the economic viability of any retrofit project. The first step, screening, offers the lowest cost and quickest assessment of a range of potential projects and allows a facility manager to prioritize which projects should be addressed first. Those that are most likely to be economically attractive, or pressing for other reasons, would then be investigated a little more deeply in a scoping study. A scoping study permits the project to obtain financial commitments from the owner or lenders before incurring the larger cost of an investment grade audit. These three assessment types are described below.

Screening

The first step in identifying a retrofit project is to screen all potential projects for their potential value. Questions to ask include: Are the energy savings likely to be substantial? Will lighting quality improvements make a difference to worker performance? Are there other benefits, in terms of maintenance costs, environmental benefits or aesthetics that may justify the cost of a retrofit?

Screening multiple projects is typically done with very rough default assumptions about the equipment and operation of lighting systems in a building. Quick "guess-timates" based on the age of the lighting system and type of building are often sufficient at this stage to rank potential projects. There are a few simple criteria to consider at this stage:

- Older lighting systems are likely to have more energy and maintenance savings potential from efficiency improvements
- Longer hours of operation will increase the value of any energy savings
- Higher energy costs will increase the value of any energy savings
- Vision-critical tasks will increase the value of lighting quality improvements. Highly paid workforces and high value products both increase the monetary significance of performance benefits from improved lighting.
- Simultaneous remodeling projects will offer opportunities for shared costs and integrated design solutions that will expand retrofit options. Historic renovations or interior remodeling both present important opportunities for lighting improvements.
- Missed lighting control opportunities often present very cost-effective retrofits, as substantial cost savings can be achieved without major alterations. Adding photocontrols to a building that already has significant daylight, or adding time or motion controls to lights that are left burning all night are easy retrofits with enormous savings potential. (Controls are discussed in chapter 8.)

Scoping Studies

A scoping study or “walkthrough” involves a rapid survey by an experienced auditor, followed by an economic analysis of the approximate energy conservation measures. To save time and money, an auditor performing a scoping study will usually only observe a sample of typical spaces within a building, to get a sense of the general type and condition of the lighting equipment and the major opportunities for a retrofit project.

A scoping study reduces financial risks by estimating the financial viability of a project before an owner makes a commitment to the more significant cost of a full audit. If the proposed project doesn’t occur, only the smaller costs are lost. A scoping study can also sometimes be sufficient to define the scope of an energy services performance contracting (ESPC) project, or can be appropriate to identify the simplest component retrofits in highly uniform buildings. A scoping study might cost on the order of $.01/ft² or less.

Investment Grade Audits

An investment grade audit is a thorough survey and engineering study supported by complete documentation. A detailed audit and evaluation might cost two or three times as much as a scoping study. The intent of the investment grade audit is threefold:

- Provide sufficient information about existing lighting equipment, energy use, and lighting quality to document the "before" condition.
- Analyze the economic potential and other benefits of proposed retrofits to optimize retrofit choices and to justify financial investment.
- Provide sufficient information to define the scope of work for the retrofit contract. An investment grade audit that analyzes more than one alternative can provide the owner with a choice of project levels to pursue.

Information collected in an investment grade audit should include:

- Detailed utility rate data and history, including time of use charges, demand, etc.
- Room-by-room, luminaire-by-luminaire equipment counts for the entire building including light level readings.
- Use of lighting loggers to determine actual operating hours and control system function.

Analysis provided in an audit report should:

- List all energy conservation opportunities, and propose one or more appropriate retrofit measures for each.
- Evaluate the energy and cost savings of each retrofit measure, using detailed cost information and taking all nuances of utility rate structure into account.
- Discuss the lighting quality, human performance, aesthetic and maintenance improvements that may be realized.
- Estimate construction budgets and life-cycle costs for alternative approaches.

5. APPLICATIONS

This chapter of the *Advanced Lighting Guidelines* includes models of advanced lighting applications. Each model is a lighting design solution to a common lighting problem or application. Applications have been developed for private offices, open offices, executive offices, grocery stores, big box retail, boutique retail, classrooms and gas stations. In most cases, more than one model has been developed to represent different design approaches or circumstances; for example, lighting for a space with daylighting versus lighting for a space without daylighting. Section 4.4 provides an overview of advanced tools and computer programs to assist lighting designers, as well as economic analysis information to help evaluate the cost effectiveness of lighting design options.

This section provides a number of models of advanced lighting design for eight types of applications:

- Private offices and small work rooms
- Open office areas
- Executive offices/conference rooms
- Grocery stores
- Big box retail stores
- Specialty stores and boutiques
- Classrooms
- Exterior – Gas stations

General Comments About the Models

- Models are intended to be simple, and they make basic assumptions about space finishes such as light-colored walls and white ceilings, medium reflectance furnishings, and a minimum of dark wall coverings and decoration. Use of dark finishes and other variations can have serious impacts on how well the particular model will work.
- Models assume modern task work equipment. For instance, flat-faced computer screens (both CRT and active matrix) are assumed. Unusual tasks, such as traditional drafting, will probably require a substantially different lighting solution.
- Models assume simple box room geometry. Complex ceiling designs and room shapes can cause significant changes in lighting performance and must be carefully addressed.

About Luminaires

Most of these designs will work well with a wide range of luminaire choices. For example, in the office models some of the designs will work with modern recessed direct, suspended indirect, or suspended direct-indirect using T-8 or T-5 technology. This was intended to encourage designers to make project-specific choices taking into account budget, appearance, and other factors. It is highly recommended, however, that the performance of a specific luminaire selection be confirmed through analysis before proceeding with a design inspired by these models.

Luminaires Cost

- The lighting equipment used in these examples is intentionally generic. The designer is encouraged to seek out products with exceptional performance to enhance the results, but as demonstrated, acceptable results will occur with relatively basic contemporary equipment. None of these models requires unique, expensive or proprietary luminaires to be successful.

- The premium for high performance luminaires over generic can run from 10% to 100% depending on quality.
- Portable lighting costs vary considerably depending on style and quality. Basic dimmable fluorescent table lamps and compact fluorescent torchieres start at around $80.

Applying Controls

In addition to making the use of lighting convenient, lighting controls can dramatically affect the amount of energy used by lighting systems. High energy costs in parts of the United States and renewed concerns about energy conservation make controls selection one of the most important steps of a lighting design. Advances in automatic controls offer a number of alternatives (controls options are discussed in detail in chapter 8). In each of the following models, the designer can choose among several controls options, depending on the priorities of the project.

Table 5-1 shows the rating scale that has been used in each model to help designers make an "advanced" choice for applicable lighting controls.

Table 5-1 – Lighting Controls Rating Scale for Models

Code	Explanation
Minimal	This control or combination of controls meets or exceeds modern energy codes, and provides a minimally acceptable level of energy efficiency with savings of at least 5–20% as compared to ordinary manual switching.
Good	This control or combination of controls represents a cost-effective controls solution, with energy savings of at least 10–30% as compared to manual switching.
Optimal	This control or combination of controls represents an optimal solution in which a minimum necessary amount of energy is used and in many cases, demand use can be managed to save cost and energy.

Controls Costs

- Dimming ballasts enable automatic daylighting control as well as manual dimming. The added cost is about $0.75/ft² for the dimming ballast and about $1.00/ft² for the daylight sensor and additional control wiring.
- A plug-strip system that uses a shelf or panel-mounted occupancy sensor costs between $100 and $250, depending on capabilities.
- The premium for an electronic ballast for metal halide lamps is presently about $40. For a 100-watt lamp, the power saving is about 13 watts, which at an energy rate of $0.10 is paid back in about 30,000 hours. The price differential is expected to drop quickly.

5.2 Private Offices and Small Work Rooms

Lighting private offices and small work rooms is one of the most common and basic lighting tasks. In addition to private and executive offices, these examples can be used to understand options for mailrooms, examination rooms, treatment rooms, work rooms, small meeting rooms and a variety of other small spaces.

Below are examples of advanced design approaches that considerably reduce lighting power below code minimums, yet provide a quality lighting system. All of these designs make liberal use of the IESNA's *Design Guide,* and tend to provide task illumination only on the desk. The ambient light level of each room is between 15 and 30 footcandles, average.

Controls

There are several controls options for private offices:

- Manual switches with a master automatic shutoff system (base case).
- For spaces with windows, provide the overhead lighting system with dimming ballast, automatic daylighting controls, and an occupancy sensor with switch for the task light.
- In addition to the above, the task light is also controlled by an occupancy sensor.
- For spaces without windows, provide a manual dimmer instead of the daylighting controls. Worker preference will result in reduced wattage, although there is no data allowing estimates of energy savings.

Energy Codes for Offices

Current U.S. energy codes and standards permit at least 1.1 W/ft² for lighting office space. Higher connected power densities are available from ASHRAE/IESNA Standard 90.1–1999 and California Title 24 building energy efficiency standards under certain circumstances.

Portable torchieres and task lighting, even using a cord and plug, should be included in the energy calculations.

Controls credits, often used to adjust for the energy saving benefits of controls, are no longer part of this calculation, except in California.

If the space is used for other purposes, different controls may be better. For instance, an occupancy sensor is almost always a good idea, but dimming in a transient workspace, like a mailroom, is probably not worthwhile. In a patient exam room in a medical office, dimming may be an excellent solution, but it may also be important to be able to turn off lights manually.

5.2.2 Private Office 1 with Window

This example of a 104 ft² typical office shows a partial task-ambient design using high performance overhead luminaires and an undercabinet task light. The overhead lighting generates more than 40 fc in the center of the room, and the task light generates in excess of 70 fc on the desk surface. Connected power is 0.97 W/ft².

For optimum daylighting, the window should include 50–70% visible light transmittance glass and horizontal or vertical blinds for individual control of direct sunlight and/or external glare sources. For a small private office 10 to 12 ft deep, 20 ft² of window area is generally sufficient for view and daylighting purposes. Extending the window up flush to the ceiling will improve daylight distribution.

Windows facing north will have the best daylight performance. East, south and west facing windows should have exterior shading to minimize sun penetration. Window glass above seven feet should have a second set of blinds controlled separately from the view window area (below 7 ft). The primary work area and computer monitor of the office space should face 45 degrees away form the window to minimize window glare on the monitor, while allowing a view out the window.

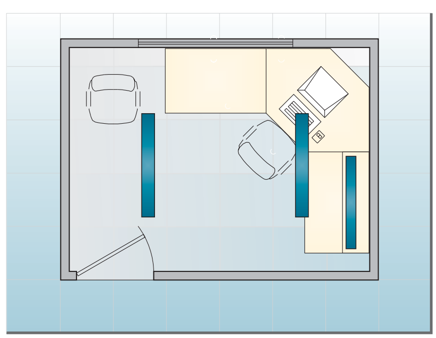


Figure 5-1 – Lighting Application, Private Office 1 with Window

Electric lighting: (2) overhead high performance luminaires, each with 1–F32T8 lamp and high light output ballast (BF >1.1, 76W) and (1) undercabinet light, 1–F25T8 (25W). Minimal control includes manual switching with automatic shutoff and an occupancy sensor. Good control includes an occupancy sensor with automatic daylight dimming. Optimal control includes an occupancy sensor with task light and plug strip control, automatic daylight dimming and user adjustable light levels. (See Table 5-1 for controls rating scale.)

5.2.3 Private Office 2 with or without Window

This example uses portable illumination exclusively. It is an excellent solution for unusual spaces in which conventional overhead lighting is impossible or undesirable. A desk lamp with a 2D or circline source provides locally high levels of light, which are usually only needed at night assuming there is sufficient task level illumination from the window. Ambient light, again needed only at night, is provided by a compact fluorescent torchiere (uplight). The ambient light level is a bit lower than other designs, about 12–15 fc. Connected power is 1.01 W/ft².

There are pros and cons to using portable lighting exclusively. The benefits include potentially lower first costs, rapid depreciation for tax benefits, and the potential for responsible energy efficiency. Drawbacks include the added load on the 120-volt system, inadvertent use of incandescent sources, and lighting becoming obstacles in the space. If portable lighting is used, the only lighting control system that meets the intent of energy codes and efficient design practices is an occupancy sensor plug strip, and unfortunately, this may demand very long cords or extensions to connect one or more lamps. Nonetheless, portable lighting should not be overlooked as a design possibility.

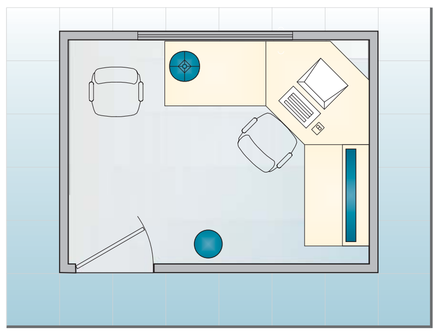


Figure 5-2 – Lighting Application, Private Office 2 with or without Window
Electric lighting: (1) desk lamp, fluorescent, 22W; (1) CFL torchiere uplight, 58W; (1) undercabinet light, 1-F25T8, 25W. Good control is the only option for this design. All lights should employ automatic shutoff devices, and the only portable system meeting this requirement is an occupancy sensor plug strip, with all luminaires plugged in. (See Table 5-1 for controls rating scale.)

5.2.4 Private Office 3 with No Window

This example shows an interior office with a single overhead recessed “indirect” luminaire or lens troffer. With two lamps in the troffer, this design produces a very uniform 22–25 footcandles of general light at 0.81 W/ft² (including the undercabinet desk light). Adding a third lamp to the overhead luminaire provides a higher overall general light level with a connected power density of 1.1 W/ft². Some occupants might prefer a table lamp to the third overhead light bulb for a similar power density.

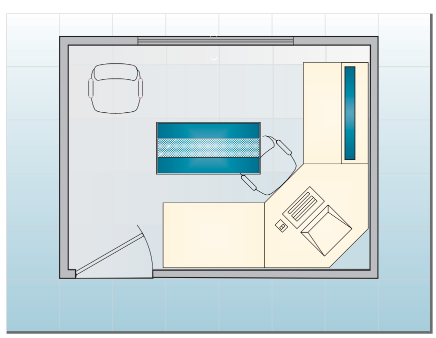


Figure 5-3 – Lighting Application, Private Office 3 with No Window
Electric lighting: (1) overhead recessed “indirect” luminaire with 2–F32T8 lamp, 60-90 W; (1) undercabinet light,1- F25T8, 25W. Possible table lamp, 22-30 W. Minimal control includes manual switching with automatic shutoff and an occupancy sensor. Optimal control includes an occupancy sensor with task light and plug strip control, and user adjustable light levels. (See Table 5-1 for controls rating scale.)

5.2.5 Private Office 4 with No Window

This design is very similar in all respects to Private Office 3, except it uses a true indirect luminaire rather than a recessed luminaire. It can also utilize a third lamp in the uplight, or a second task light in the form of a table lamp. Power density is 0.81 to 1.1 W/ft². This design requires a light-colored ceiling.

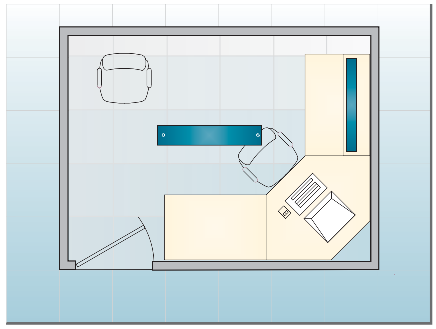


Figure 5-4 – Lighting Application, Private Office 4 with No Window
Electric lighting: (1) overhead uplight luminaire with 2–F32T8 lamps, 60-90 W; (1) undercabinet light, 1-F25T8, 25W. Possible table lamp, 22-30 W. Minimal control includes manual switching with automatic shutoff and an occupancy sensor. Optimal control is an occupancy sensor with task light and plug strip control, and user adjustable light levels. (See Table 5-1 for controls rating scale.)

5.2.6 Private Office 5 with or without Window

This group of designs (5 through 8) uses some of the same ideas as 1 through 4, but with a significantly different furniture plan. There is no undershelf task light in this model. Example 1-5 is illuminated totally with portable lighting. Connected power is 0.98 W/ft². Automatic daylighting control is not possible with this design.

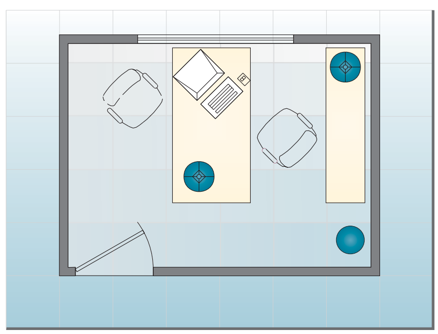


Figure 5-5 – Lighting Application, Private Office 5 with or without Window
Electric lighting: (2) table lamps, 22 W each; (1)compact fluorescent torchiere, 58W. Good control is the only option for this design. (See Table 5-1 for controls rating scale.) All lights should employ automatic shutoff devices, and the only portable system meeting this requirement is an occupancy sensor plug strip, with all luminaires plugged in.

5.2.7 Private Office 6 with Window

An uplight mounted to the wall behind the worker produces ambient light favoring the worker's end of the room. A table lamp provides task illumination. This design requires a light-colored ceiling.

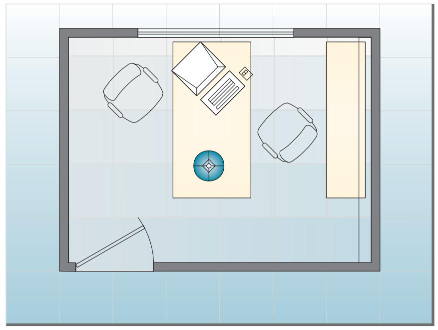


Figure 5-6 – Lighting Application, Private Office 6 with Window
Electric lighting: (1) table lamp, 30 W; (1) wall-mounted uplight, 2–F32T8, 68W. Good control is the only option for this design. (See Table 5-1 for controls rating scale.) All lights should employ automatic shutoff devices, and the only portable system meeting this requirement is an occupancy sensor plug strip, with all luminaires plugged in.

5.2.8 Private Office 7 with Window

This design is similar to Private Office 3. Without a task lamp, 3 lamps are needed for this luminaire. Connected lighting power is 0.86 W/ft². Consider also using a two-lamp overhead luminaire and a portable desk light for about the same power density.

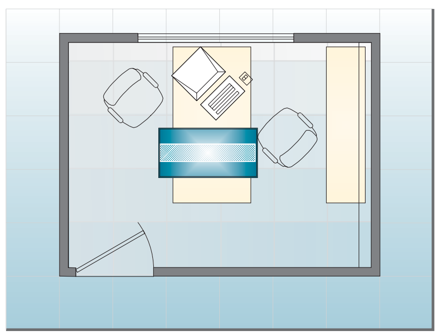


Figure 5-7 – Lighting Application, Private Office 7 with Window
Electric lighting: (1) overhead recessed "indirect" luminaires with 3–F32T8 lamp, 90 W; or 2-lamp overhead luminaire and task light, 22-30 W. Minimal control includes manual switching with automatic shutoff and an occupancy sensor. Good control includes an occupancy sensor with automatic daylight dimming. Optimal control includes an occupancy sensor, automatic daylight dimming and user adjustable light levels. (See Table 5-1 for controls rating scale.)

5.2.9 Private Office 8 with Window

This example is the same as example 1-7, except that it uses a suspended indirect luminaire.

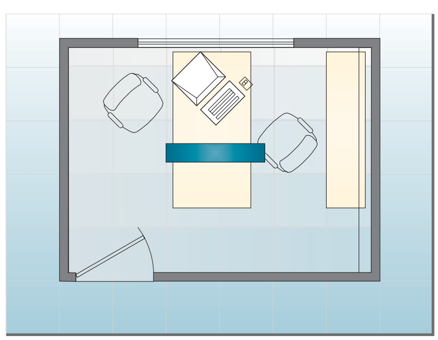


Figure 5-8 – Lighting Application, Private Office 8 with Window
Electric lighting: (1) overhead suspended "indirect" luminaire with 3–F32T8 lamp, 90 W; or 2-lamp overhead luminaire and task light 22-30 W. Minimal control includes manual switching with automatic shutoff and an

occupancy sensor. Good control includes an occupancy sensor and automatic daylight dimming. Optimal control includes an occupancy sensor, automatic daylight dimming and user adjustable light levels. (See Table 5-1 for controls rating scale.)

5.3 Open Office Areas

Lighting for open office areas is extremely important because of the proliferation of this type of space. Significant energy savings can be realized because of the large percentage of the economy working in this environment. The following three example designs show advanced approaches to considerably reducing lighting power below code minimums. Like the previous examples, these designs make liberal use of the IESNA Design Guide, and tend to provide task illumination only on the desk. The ambient light level of each room is between 15 and 30 footcandles, average.

Daylighting

Many open office areas are designed to take advantage of windows, at least for view. To take full advantage of natural light in these spaces, consider the following:

- Increase window height to match the ceiling height if possible.
- Increase ceiling height as much as possible. In many cases, the use of suspended lighting instead of troffers often permits 6 in. or more increase in ceiling height. Increased ceiling height improves the uniformity of indirect lighting and penetration depth of daylighting.
- Ensure that some type of mechanical shading device is used for east, south and west exposures. North exposures can also introduce too much natural light for computer work, especially near the windows, so be prepared to introduce operable shading for most windows.
- If possible, ensure that the glazing system has appropriate attenuation of natural light. Keep in mind that natural light can be overwhelming for even the brightest computer monitor. In general, visible light transmission between 35% and 50% has been identified as a reasonable combination of clarity and attenuation.
- Add toplighting for top floors and single-story buildings.

Task Lights

This particular design assumes a single 25-watt task light per workstation. Keeping in mind that a task light occurs every 100 ft² or so, it's critical to ensure that the lowest possible task light watts are being used. For a 36 in. to 42 in. task light, the lowest possible source power is around 25 watts regardless of technology (T-8, T-5 or T-2). Most task lights produce more than the necessary amount of light, so dimming is at least suggested both to control luminance and save energy.

Controls

Basic energy codes generally require automatic shut off of the overhead lighting system, which is typically provided by a "sweep" switching system. In a typical open office design, one or more local override switches would be connected to a relay that is also controlled by a time of day program. Some energy codes might require a separate switching zone for the daylit area near the window.

More powerful controls can be added to save considerable energy. Most importantly, the luminaires closest to the windows can be controlled by daylight dimming, and all troffers can be dimmed for adaptive compensation. This feature alone can easily save 10–50% of the lighting energy and reduce on-peak demand.

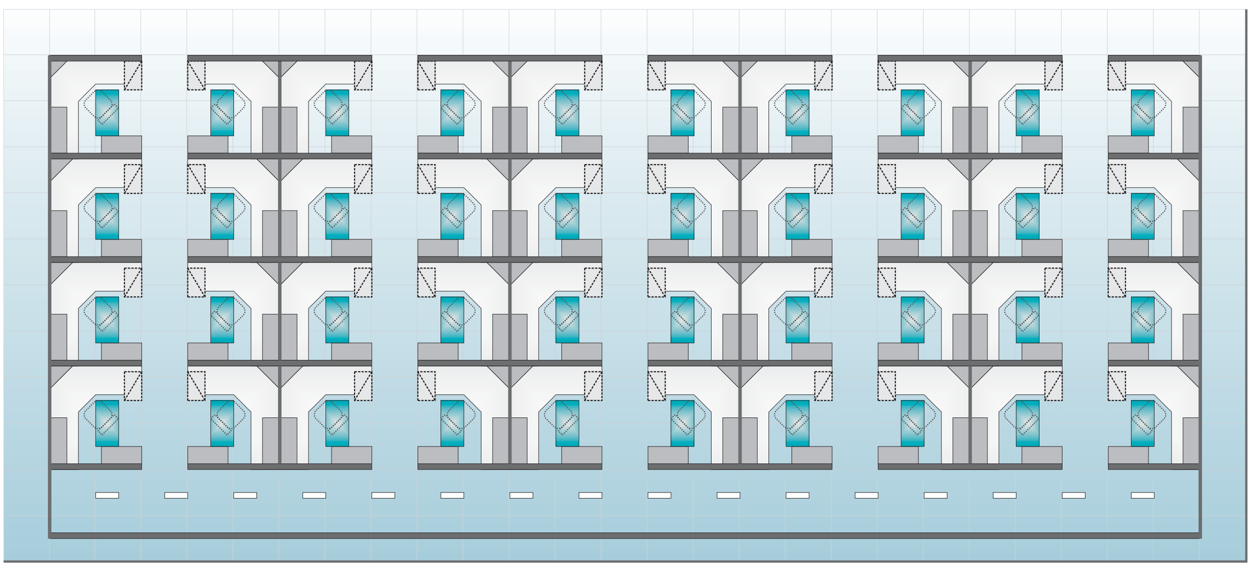
Overhead motion sensing can actually be difficult in this type of space, and the energy savings are best realized only in facilities with unusual work hours and patterns. However, a plug-strip occupancy sensor at each workstation controls task lights and appliances and can save 10–30% of the energy used by task lights as well as computer monitors, laser printers, and other powered devices. Lights in the core circulation area are also equipped with dimming ballasts, and all lighting can be controlled by an adaptive compensation system that dims overhead lighting at night. Note that the system that provides adaptation-compensating dimming (saving 5–50% of off-peak energy depending on night operations) also permits time of day load shedding.

5.3.2 Open Plan Offices, Lay-in Troffers

This design shows an optimized layout meeting IESNA recommendations for light levels at a minimum of energy use. Ordinary troffers are used at each workstation. Adequate ambient light levels are generated in the circulation areas, and the overhead luminaires employ 2 lamps even though the spacing is an unusually wide 8 ft x 12 ft. However, for this design to work, it's essential that the luminaires occur over the workstation as shown and be supplemented with task lights. In the circulation area, a design employing wall-washing is shown. Its power use is consistent with the overall design, and it provides an excellent balance to the bright window wall.

Despite the extremely low cost of moving troffers in most cases, open plan furniture designs seldom optimize troffer layouts to the furniture layout. With this design approach, it is critical that the lights be repositioned if major changes are made to the space layout.

When using troffers, consider individual dimmers for each workstation. Studies show a strong preference for differing light levels depending on the type of work being performed. In particular, workers doing intensive computer work, especially workers performing high-resolution screen work, benefit significantly from the ability to control general light. Dimmers with handheld controllers are typically employed to reduce wiring and costs. This design has a connected power of 0.89 W/ft².



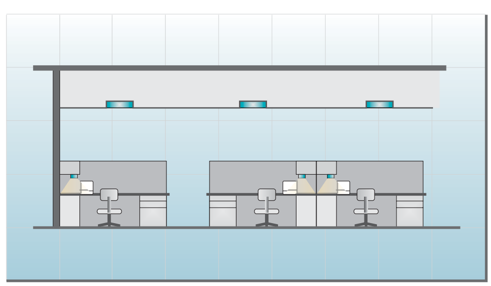


Figure 5-9 – Lighting Application, Open Office 1

Electric lighting: A single 2-lamp recessed troffer is located over workstation. The circulation area is illuminated by wall-washers (bottom) using FT40 lamps that also serve to balance interior surface luminance. Minimal control includes manual switching with automatic shutoff, multiple occupancy sensors, and relays for daylit zones and non-daylit zones, with override switches. Good control includes manual switching with automatic shutoff and automatic daylight dimming. Optimal control includes manual switching with automatic shutoff, *automatic daylight zone dimming, individual workstation dimming and occupancy sensor with task light and plug strip control. (See Table 5-1 for controls rating scale.)*

5.3.3 Open Plan Offices, Uplighting

This design represents the rapidly growing field of general indirect lighting for offices. Rows of indirect lights are spaced at 10 ft and use a single T-8 lamp with high light output ballast, generating 20–30 fc in an empty room. This design also employs a continuous wall slot to illuminate the core wall, using a single T-5 or T-8 standard lamp. As above, it balances the window brightness of the opposite wall. The connected power density is about 1.05-1.10 W/ft². The designer might also consider a low ambient design using a single T-5 standard lamp in the uplight, dropping the connected power to 0.88 W/ft² and the night ambient light level to around 15–20 fc, but additional task light may be needed as in example 2-3.

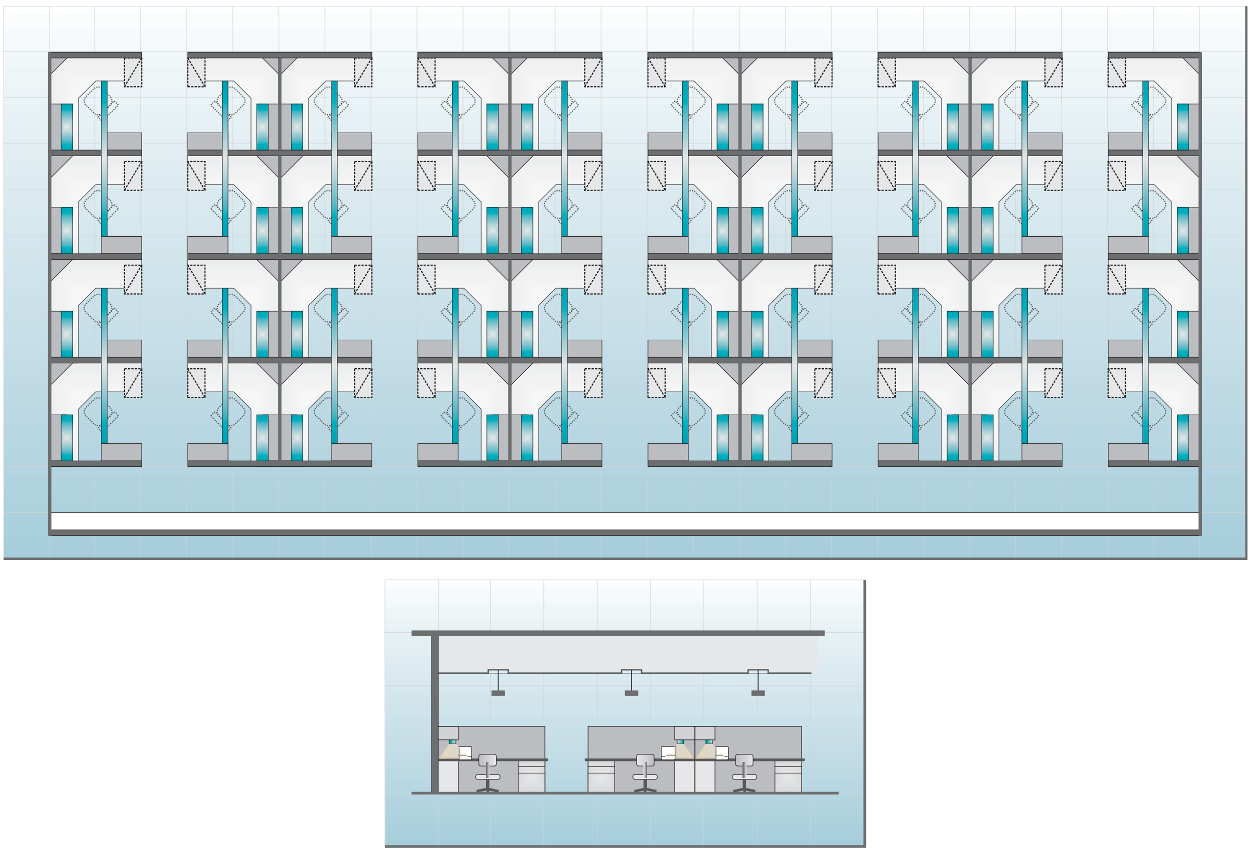


Figure 5-10 – Lighting Application, Open Office 2

Electric lighting: A single T-8 lamp with high light output ballast in each suspended luminaire section. Wall slot along circulation core employs standard T-5 or T-8 lamps. Minimal control includes manual switching with automatic shutoff; multiple occupancy sensors and relays for daylit and non-daylit zones, both with override switches. Good control includes manual switching with automatic shutoff and automatic daylight dimming. Optimal control includes manual switching with automatic shutoff, automatic daylight zone dimming, two zone overhead dimming for tuning and an occupancy sensor with task light and plug strip control. (See Table 5-1 for controls rating scale.)

5.4 Executive Offices/Conference Rooms

Executive offices and conference rooms can also be lighted with greater efficiency. Although they don't represent as much area as standard office types, these spaces are nonetheless important in carrying out an organization's energy efficiency mission. All of the models represent spaces that are about 225 ft², large enough for a senior executive office or small conference room. This plan shows the room set up with desk and credenza near the window, and a small round meeting table located near the entry door.

This model was specifically developed with a window capable of providing only a modest amount of daylight. If the space is used as an executive office, the daylight is plentiful in the work area, and the window and its view are provided to the occupant when working at the credenza. When the room is used as a conference room, the daylight is a feature of the room but will probably not provide task illumination. Also, it may be necessary to employ blinds to permit the conference room to be used for audio-video presentations.

Controls

In all of these designs, automatic daylight dimming can be used for the whole room, and it can be combined with a ceiling-mounted occupancy sensor and wall mounted two-zone dimmer for maximum flexibility.

5.4.2 Executive Office/Conference Room 1

This example employs two rows of single lamp T-8 luminaires, with a high ballast factor ballast to drive the lamp to about 3450–3500 lumens. Each luminaire can be:

- recessed lensed, parabolic or recessed “indirect"; or
- suspended indirect, semi-indirect, or direct-indirect.

Luminaires should be modern, high performance types with at least 70% efficiency. The lighting quality of the room will of course vary depending on the luminaire choice. Direct lighting systems, including the so-called recessed “indirect,” will tend to produce higher task illumination levels, but with darker ceilings and upper walls. Suspended lighting systems will tend to better illuminate upper walls and ceilings, but with a lower average footcandle level. Maintained general illumination levels will be between 25–35 footcandles. Connected power is about 0.75 W/ft². Consider a table lamp for the executive desk or credenza; it’s only about 0.13 W/ft².

Designers should note that the layout of this room is far from ideal. For instance, from a daylighting perspective, the room would work better if a long wall, rather than a short wall, were the window wall. Also, it would be preferable to rotate the office desk 90 degrees so that the occupant would look to the side to view the window, thus enabling the view axis of the computer to be parallel to the window. However, this model was taken from a recent project and represents typical contemporary space planning and layout.

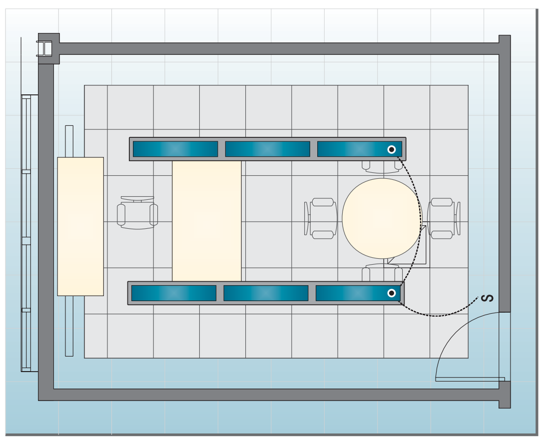


Figure 5-11 – Lighting Application, Executive Office/Conference Room 1

Electric lighting: Two rows of single lamp T-8 luminaires with high ballast factor ballast (BF=1.2). Minimal control includes manual switching with automatic shutoff; occupancy sensor and relays with manual override switches for daylit and non-daylit zones. Good control includes manual switching with automatic shutoff and automatic daylight dimming. Optimal control includes two-zone manual dimming with automatic daylighting control and occupancy sensor; two-zone manual override switching with occupancy sensor and relay, and automatic daylight dimming, and occupancy sensor-controlled task light and plug strip. (See Table 5-1 for controls rating scale.)

5.4.3 Executive Office/Conference Room 2

This is a modest general lighting design, probably best for a conference room use. Each recessed “indirect” luminaire employs a single F40T5 twin-tube lamp, and the result is a pleasant 40–50 footcandles. The connected power is 1.01 W/ft².

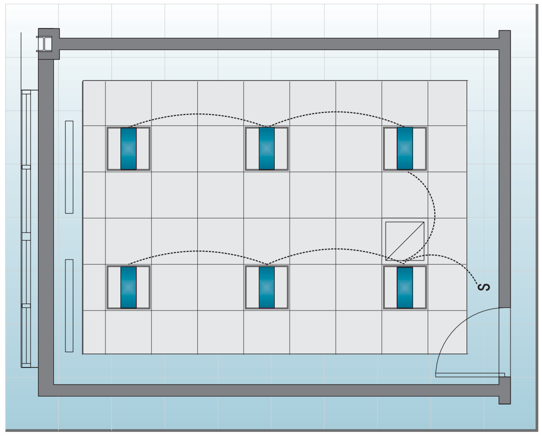


Figure 5-12 – Lighting Application, Executive Office/Conference Room 2
Electric lighting: High-performance recessed "indirect" luminaires, each employing 1–F40T5 twin-tube lamp. Minimal control includes manual switching with automatic shutoff, an occupancy sensor, and relays with manual override switches for daylit and non-daylit zone. Good control includes manual switching with automatic shutoff and automatic daylight dimming. Optimal control includes two-zone manual dimming with automatic daylighting control and occupancy sensor; two-zone manual override switching with occupancy sensor and relay, automatic daylight dimming, and an occupancy sensor-controlled task light and plug strip. (See Table 5-1 for controls rating scale.)

5.4.4 Executive Office/Conference Room 3

Many building tenants prefer the drama and elegance of downlighting in their executive spaces. This design uses 18-watt triple tube downlights with dimming ballasts, automatic daylighting control, motion sensing and manual dimming. Downlight wall-washers can be used on the top and bottom rows for increased vertical surface illumination. The power density is 1.07 W/ft². Add a table lamp, and the connected power is about 1.2 W/ft².

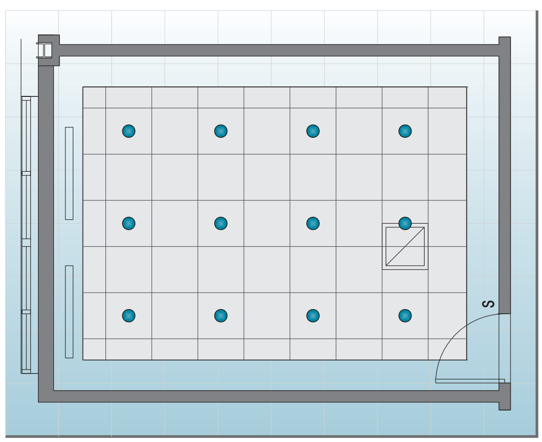


Figure 5-13 – Lighting Application, Executive Office/Conference Room 3
Electric lighting: High-efficiency downlight with 18 W triple-tube lamp. Minimal control includes manual switching with automatic shutoff, an occupancy sensor, and a relay with manual override switches for daylit and non-daylit zones. Good control includes manual switching with automatic shutoff and automatic daylight dimming. Optimal control includes two-zone manual dimming with automatic daylighting control and occupancy sensor; two-zone manual override switching with occupancy sensor and relay, automatic daylight dimming, and occupancy sensor-controlled task light and plug strip. (See Table 5-1 for controls rating scale.)

5.4.5 Executive Office/Conference Room 4

This is a new design concept that works especially well for illuminating the sidewalls of the space. Rows of single T-8, asymmetric recessed "indirect" luminaires produce good vertical surface lighting, with an acceptable illumination of 30–40 fc. But because the luminaires are only mildly asymmetric, this design also produces good task lighting. Using a high ballast factor ballast, the connected power for this design is 0.75 W/ft². Adding a table lamp or two would still result in an energy efficient—and attractive—solution that can brighten the walls.

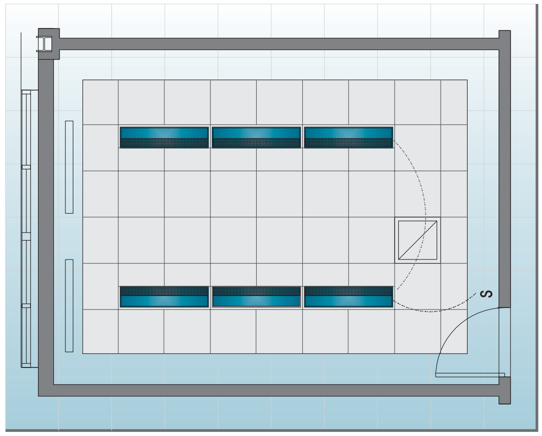


Figure 5-14 – Lighting Application, Executive Office/Conference Room 4
Electric lighting: Rows of single T-8 lamps and high ballast factor ballast (BF=1.20) in high efficiency, asymmetric recessed "indirect" luminaires. Minimal control includes manual switching with automatic shutoff and occupancy sensor and relay with manual override switches for daylit and non-daylit zones. Good control includes manual switching with automatic shutoff and automatic daylight dimming. Optimal control includes two-zone manual dimming with automatic daylighting control and occupancy sensor; two-zone manual override switching with occupancy sensor and relay, automatic daylight dimming, and occupancy sensor-controlled task light and plug strip. (See Table 5-1 for controls rating scale.)

5.5 Grocery Stores

To design the lighting for a grocery store, consider the following:

- The objective is to produce vertical illumination in most of the store. Horizontal footcandles in the aisle only illuminate the floor.
- The exceptions are the checkout area and produce, and perhaps, the bakery or other special sales areas. In these areas, comparatively high light levels are generally important.
- There are many self-illuminated cases, usually refrigerated. While the lighting power may not be included in energy calculations, the integration of these fixtures into the overall design is very important.
- The advent of "departments," such as the bakery, wine, floral or deli, tends to demand an architectural and lighting "theme" for each.
- Brightness appears to be more important than visual comfort. Passersby appear to be attracted by bright interior illumination, serving as a sign that the store is open for business.
- High light levels may appear to reinforce themes of cleanliness.
- Modest lighting systems, such as strip lights, appear to reinforce themes of cost consciousness. Sophisticated lighting solutions, especially those employing glare control or attractive luminaires, may reinforce themes of exclusivity and high price.

To illustrate advanced lighting choices, two different designs for a grocery store are provided. The store represented here is a collage of current designs. It is a modest sized store (20,000 ft², as compared to superstores exceeding 60,000 ft²); it has a themed style, with distinctive produce, bakery, wine, pharmacy/toys, and checkout "areas" along with a majority of traditional aisles; and it is marketed at an average suburban marketplace. Simple variations could also address the urban "loft" market and a more casual "marché" (market) style.

5.5.1 Grocery Store with no Daylighting

This example shows a basic striplight design with a solid roof and no daylighting. This design, which is classic grocery store lighting, uses striplights (or “supermarket trough lights”) perpendicular to the aisles. Acceptable vertical surface illumination in the aisles is achieved by brute force. The high efficacy and high efficiency of the strip lights produce abundant vertical and horizontal illumination. To surpass the energy criterion of most codes, this general lighting system should be absolutely state-of-the-art, employing T-8 standard or high output lamps and electronic ballasts. This particular design uses T-8 standard lamps and high ballast factor ballasts. Grocery chains seem to favor exposed lamps; customers tend to relate good quality lighting with increased cost, and thus bare lamps seem to appeal to cost consciousness among shoppers. If the store has windows, bright lights are also a form of sign, informing potential customers that the store is open for business.

The perimeter of the store employs a continuous fluorescent valance or uplight (possibly both). This light provides luminance balance and is often used to illuminate signs on the uppermost wall above the goods. Especially if used as an uplight, this is an excellent application for the T-5 lamp, as it permits a very small cove luminaire.

The themed aspect of the design is achieved in “departments.” It includes compact fluorescent or low wattage metal halide luminaires for lighting in specialty departments described above. These luminaires will usually be pendant downlights in a style that reinforces the theme of the store, such as a prismatic glass or acrylic shade in a “marché” (market style) design. A 26- or 32-watt triple tube lamp with shield is a good choice for smaller luminaires; a 70- or 100-watt metal halide lamp can be used in larger luminaires illuminating a larger area. Often different lights are used in each department to create identity and perhaps reinforce a minor theme, such as industrial shade pendants over a bakery counter. It is extremely important to choose the luminaire carefully so that its high efficacy source does not ruin the illusion. In this design, themed pendants are used:

- over the checkout, toys, bakery and card shop (metal halide 100-watt pendants); and
- for the wine and deli (32-watt triple tube pendants).

The prismatic ribbed glass or acrylic shade is exemplary at producing useful downlight as well as some ambient light and a visible light source when viewed from a distance, such as through the store window. The ability of the passerby to see illuminated lights appears critical in determining whether or not a store is open. The area closest to the window offers an obvious opportunity to create the effect with a minimum of energy use and light waste.

Often the produce area is lighted with a different lighting system from the rest of the store. In this design, track lighting using metal halide lamps is used to dramatically illuminate the produce gondolas, and fluorescent valance lights are used to illuminate the produce in refrigerated misting wall fixtures. Other lighting systems for the produce area might include suspended fluorescent direct lighting systems or larger industrial luminaires with metal halide or compact fluorescent lamps.

Power Density

In general, energy codes exclude the lighting within refrigerated cases. The design shown here, not including refrigerated case lighting, has a connected lighting power of about 1.4 to 1.5 W/ft^2. Lower power density might be achieved by eliminating the perimeter cove or valance, but this decision should be carefully evaluated in connection with the layout of the general lighting system.

Controls

The type of control suited for a grocery store first depends on the planned hours of operation, including both sales and shelf stocking time. Recommended controls options include:

- Multilevel switching using alternating lamps or ballasts. Lower light levels can be used during stocking periods. Not recommended for stores that are open seven days a week, twenty-four hours a day, because extinguished lamps suggest the store is either closed or poorly maintained. As compared to single level switched lighting, this approach can save 5–25% of lighting energy.

- Dimming throughout all areas. Lower light levels can be used from sunset to sunrise, possibly in stages (for example, brighter light levels from sunset to 11:00 PM, and lower light levels from 11:00 PM until dawn). Fully utilized, this approach can save 25–35% of lighting energy.
- Daylight zone dimming if there are large windows. This can save 5–15% of on peak lighting energy.

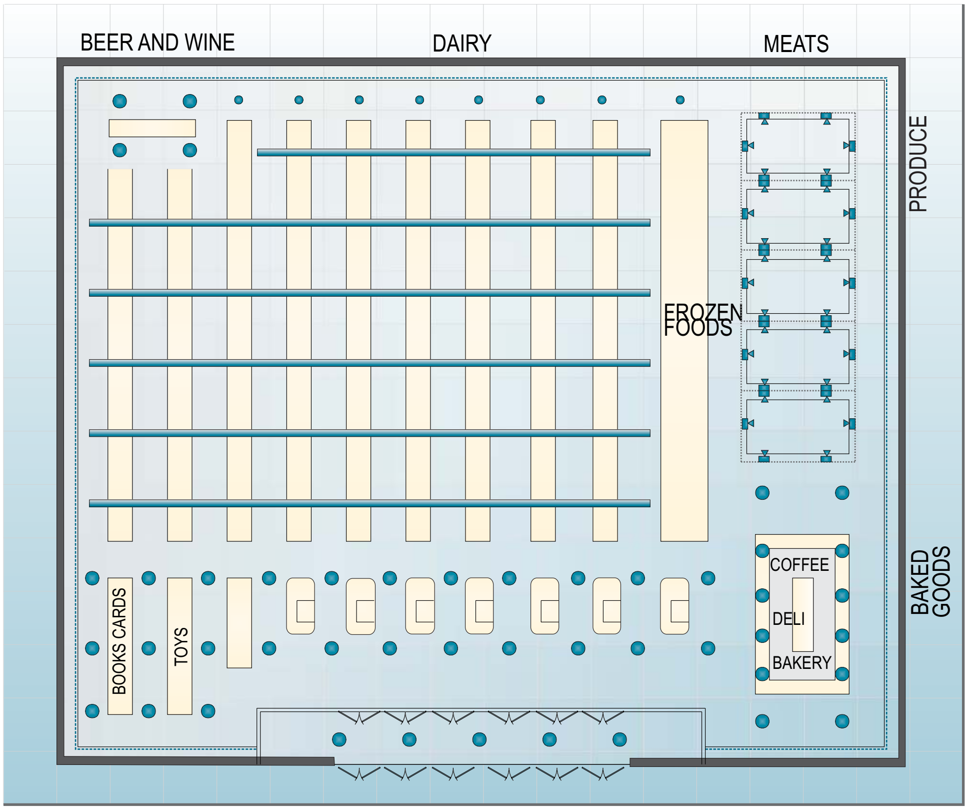


Figure 5-15 – Lighting Application, Grocery Store with No Daylighting
Electric lighting: F59T8 luminaires with high ballast factor ballasts; 70 W low-UV metal halide track spots for produce; 100 W metal halide downlights for check out, cards, toys and bakery (no tall store fixtures); 32 W compact fluorescent pendant lights for wine and deli; T-8 lamps and low ballast factor ballasts in cove lights for perimeter valance. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different day and night light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.5.2 Grocery Store with Daylighting

This design is a two-component (task and ambient) design in which task lighting is built into all of the shelving displays. Using the latest T-5 lamp technology, the shelving valance produces relatively high vertical illumination on shelves, but much lower light levels on the floor result. By day, ambient light is mostly provided by daylight, and the overall light levels approximate the electric-only lighting system in the first design. By night, the shelving areas utilize the perimeter cove lighting for ambient and general illumination, which will then be much lower. The majority of the store has this natural, day/night cycle that saves energy and is believed to be preferred by shoppers.

Similarly, daylight in the produce area increases ambient light by day. This permits fewer track lights so the overall electric lighting in this area is much lower in power than typical non-daylit space. The checkout and specialty departments use the same layout but lower lamp watts (70 W) than the standard store; this will create a sense of brightness to invite nighttime shoppers and assure adequate task lighting for critical shopping areas, but also relies upon daylight for some of its daytime light level.

Daylighting

The daylighting design for this store assumes that there is no suspended ceiling in the center of the building (although there may be a soffit at the perimeter around 14 ft above finished floor). Depending on the location, utility rate, etc., the results will differ slightly, but about 4% of the roof area is about average for the amount of fenestration area using high performance prismatic skylights with shallow white-painted wells having 45 degree cutoff. Use SkyCalc or other analysis software to determine the exact skylighting scheme for a particular design (see section 4.4.2).

Using 4% skylight-to-roof ratio (SRR) and 73% transmitting prismatic skylights, this design employs 15 modular skylights (4 ft x 8 ft), spaced about 20–30 ft on centers, with a ceiling height of 21 ft. Using white bubble skylights will increase the number of skylights by 50%, which may not be advisable in extreme climates.

Special note: Avoid skylights over checkout counters due to the possible interference with checkout scanning equipment.

Power Density

This design, not including refrigerated case lighting, has a connected lighting power of about 1.2 to 1.4 W/ft^2. Lower power density levels will be hard to reach without sacrificing critical illumination systems.

Controls

As with the other example, controls choices depend on the planned hours of operation, including both sales and shelf stocking time. Consider dimming throughout all areas, including task lights. Lower light levels can be used from sunset to sunrise (adaptive compensation), possibly in stages (for example, brighter light levels from sunset to 11:00 PM, and lower light levels from 11:00 PM until dawn). Fully utilized, this approach can save 15–25% of lighting energy.

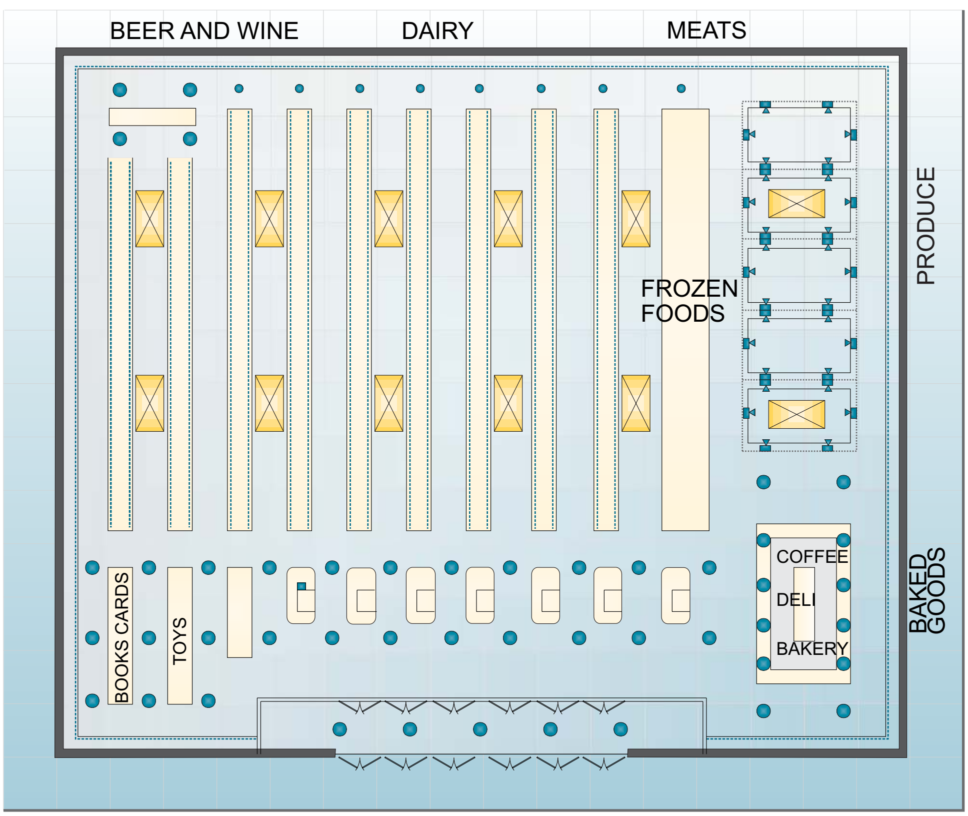


Figure 5-16 – Lighting Application, Grocery Store with Daylighting

Daylighting: Modular skylights. Electric lighting: T-5 linear task lighting built-in to store fixtures; 70 W low-UV metal halide track spots for produce; 70 W metal halide downlights for check out, cards, toys and bakery (no tall store fixtures); 32 W compact fluorescent pendant lights for wine and deli; T-5 cove lights for perimeter valance. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different day and night light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with daylighting, adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.6 Big Box Retail Stores

"Big box" stores include a variety of retail establishments, from the smaller office supply, household, consumer electronics and appliance stores (10–20,000 ft²) to much larger stores including building materials, warehouse goods and general merchandise (over 100,000 ft²). They tend to be characterized by open exposed structures, exposed HVAC ductwork, roof/ceiling heights of 20–30 ft; and maximum display/storage warehouse rack height of around 12–14 ft. This model is a small store (12,000 ft², based on an actual design for a big box appliance store.

The growth in the "big box" market makes this a critical area for lighting energy efficiency. Energy codes allow around 1.8 W/ft² or more for retail lighting, but because big box stores permit the use of relatively efficient equipment, more efficient designs are possible.

5.6.1 Big Box Store with Daylighting

A big box store with daylighting is generally approached using metal halide industrial downlights. However, these downlights are a poor match for the narrow aisle lighting problem that occurs among stacks. In this example, metal halide downlights are used for open areas, but in between stacks, fluorescent systems are used instead. This particular model includes track lighting for boutique feature displays and store window lighting, specialty compact fluorescent pendant lights for the boutique area floor, and specialty fluorescent linear lighting for a feature sales area near the store front.

See the discussion of daylighting in Grocery Store with Daylighting above; many of the considerations apply, including eliminating skylights over the checkout area.

With electronic ballasts used for the metal halide lamps, this design operates at about 1.5 W/ft². With dimming controls on all fluorescent lighting, the average power could be reduced by 20–30% through daylighting and adaptive compensation. Rather than harvest daylighting directly, this design simply uses daylight to supplement a slightly lower than normal electric lighting level. Consider a bilevel metal halide control for stocking and other work during non-business hours.

Designers should consider other options to metal halide luminaires in order to extract maximum energy efficiency. Depending on store design and ceiling height, the following options might also work:

- Industrial-style luminaires, similar in appearance to metal halide but employing multiple compact fluorescent lamps. Direct benefits include improved color rendering, possible dimming and straightforward multiple level light switching.
- High-bay T-5 high output luminaires, employing reflectors to direct light downward. This is a relatively new idea, designed to take advantage of the high mean lumens per watt of the T-5 system (over 90) as compared to the 60-65 mean LPW of either metal halide or compact fluorescent options. With electronic dimming ballasts, this approach appears to offer the maximum potential for energy efficiency, and has superior color, lumen maintenance, and lamp life as compared to other options.

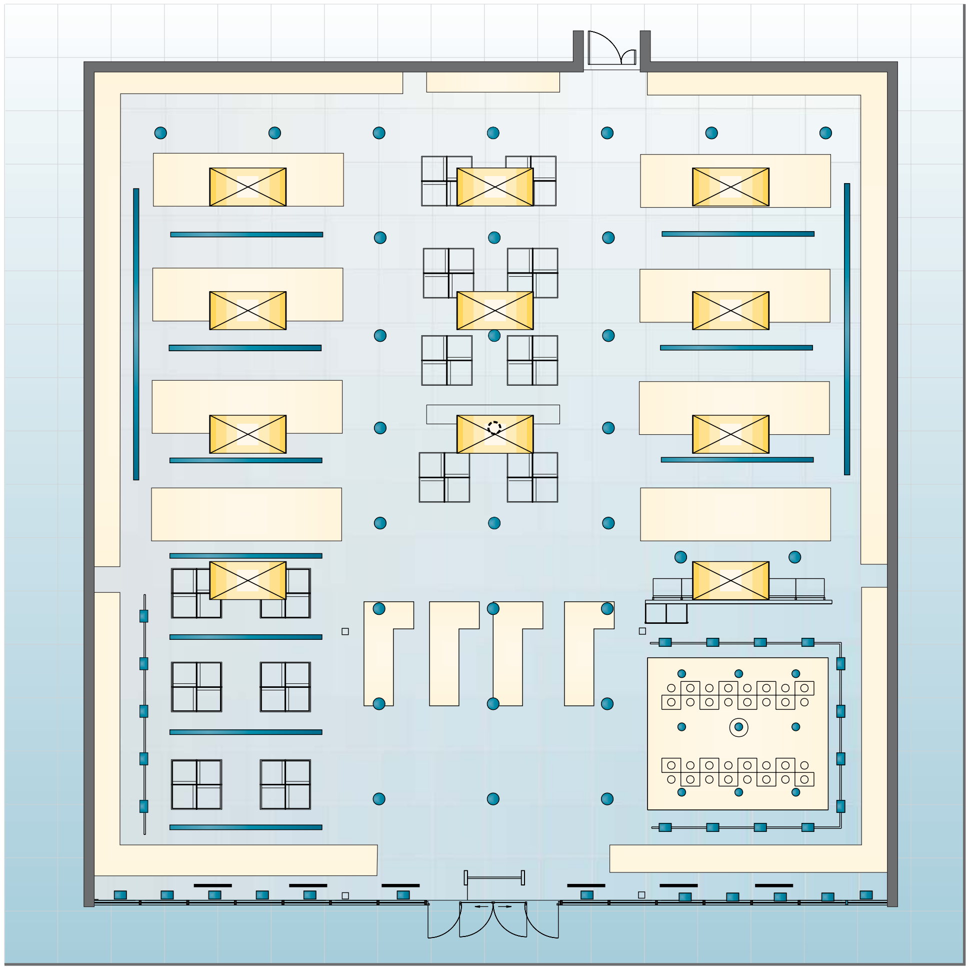


Figure 5-17 – Lighting Application, Big Box Store with Daylighting

Daylighting: Modular skylights. Electric lighting: 100 W metal halide industrial-style downlights; 100 W metal halide track floodlights; single-lamp continuous row F59T8 aisle lights; two-lamp continuous row F32T8 luminaires for low fixture display area; dual 40 W T-5 twin tube floodlights in store window for posters; 42 W compact fluorescent pendant lights for boutique area. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different day and night light levels. Optimal control includes multiple level HID/ dimmed fluorescent and compact fluorescent luminaires, with daylighting, adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.6.2 Big Box Store without Daylighting

This design is similar to the example above except that it has no skylights. Since skylights work so well in this application, these situations will probably be limited to stores selling computers and televisions where the relatively high light levels of natural light might be a detriment to selling. To compensate, higher wattage metal halide downlights are used, increasing the connected load to 1.6 W/ft².

With dimming controls on all fluorescent lighting, the off-peak energy use could be reduced by 20–30% through adaptive compensation. Additional energy savings may be possible by dimming metal halide lamps but color-rendering considerations may make this less desirable.

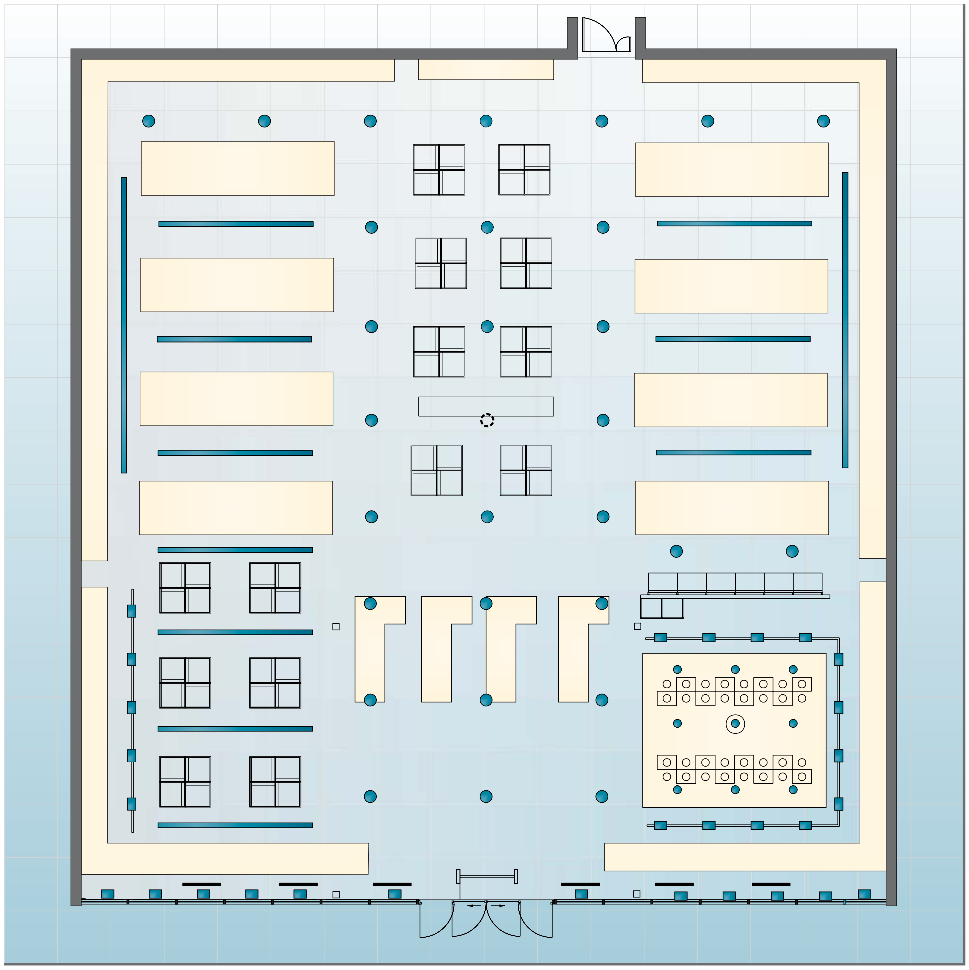


Figure 5-18 – Lighting Application, Big Box Store without Daylighting
Electric lighting: 150 W metal halide industrial-style downlights; 100 W metal halide track floodlights; single-lamp continuous row F59T8 aisle lights; two-lamp continuous row F32T8 luminaires for low fixture display area; dual 40 W T-5 twin tube floodlights in store window for posters; 42 W compact fluorescent pendant lights for boutique area. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different day and night light levels. Optimal control includes multiple level HID/dimmed fluorescent and compact fluorescent luminaires, with adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.7 Specialty Stores and Boutiques

The three designs shown in this section use the footprint of a typical mall shop with three different occupants and lighting designs. All are based on a single "bay" of a modern retail mall.

Most energy codes provide additional power for specialty stores and boutiques, through customized calculations of allowed power. The challenge of advanced lighting is to create appealing designs under 2.0 W/ft².

Adding daylighting into mall stores is an interesting possibility. In single-story malls and for the upper floor of larger malls, skylights could be very effective additions, as shown in previous examples. Both energy savings and benefits in retail lighting will result. Designers are encouraged to "break the mold" and investigate adding skylights even in the most typical mall stores.

5.7.1 Specialty Store, Coffee or Delicatessen

This design is typical of the “look” of the coffee and juice boutiques that are so prevalent in contemporary retailing. Decorative lighting plays a critical role in reinforcing the theme of the design, with large pendants providing general illumination and smaller pendants producing illumination over the countertops using compact fluorescent lamps. The work area and menu board behind the service counter employ F40T5 twin wall-washers. The merchandise and feature displays around the store are highlighted using MR-16 IR accent lights. Daylighting enters through the storefront only. The connected power for this design is 1.9–2.0 W/ft² depending on specific luminaire and lamp selections. Dimming can be added to save energy through adaptive compensation to reduce watts at night and as needed.

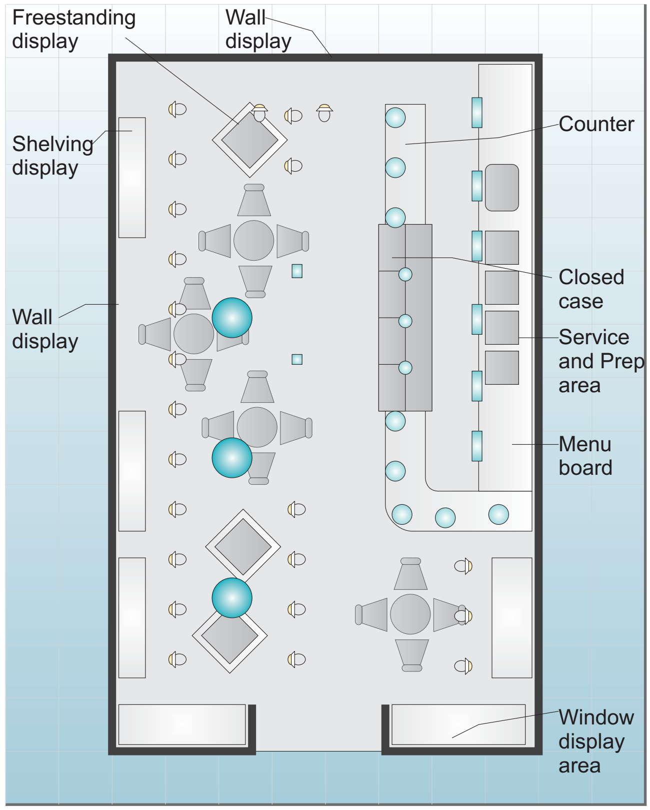


Figure 5-19 – Lighting Application, Specialty Store, Coffee or Delicatessen

Electric lighting: (4) large decorative pendant lights with compact fluorescent lamps provide ambient light; low-voltage accent lights for displays using 37 W MR-16 IR lamps; compact fluorescent pendant lights over counter; track lights in windows employ 37MR-16 IR lamps; wall-washers behind counter illuminate work area and menu board using F40T5 twin tubes and 0.85 BF ballasts. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different day and night light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.7.2 Retail Store, Boutique or Gifts

This design is typical of the youth-oriented style popularized by stores like Old Navy. It employs suspended fluorescent general lighting luminaires with some highlighting and a few pendant luminaires for theme reinforcement. Most of the design employs fluorescent lighting: the suspended linear fluorescent luminaires use T-5HO or dual T-8 lamps; the downlighting at the entry uses compact fluorescent lamps; and the pendants are compact fluorescent. There are only a few MR-16 IR display lights in the store window and on the vertical panel behind the point-of-sale to illuminate posters and key displays. Daylighting enters through the storefront only.

By optimizing the power of individual luminaires, this design squeaks by the power limit of 2.0 W/ft².

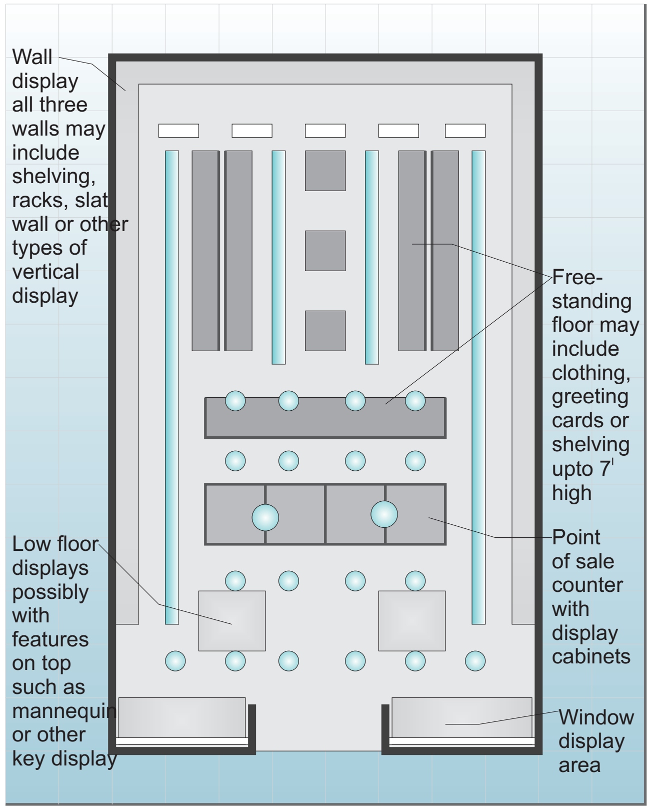


Figure 5-20 – Lighting Application, Retail Store, Boutique or Gifts

Electric lighting: General illumination using stylish suspended fluorescent luminaires with (1) T-5 HO lamp; 32 W compact fluorescent downlights at entry; 32 W compact fluorescent pendant lights over counter; MR-16 IR lamps accent lights at point-of-sale; 37MR-16 IR lamps in track lights in windows; FT40T5 twin tubes with .85 BF ballasts for wall-washers at back wall. Minimal controls include basic switching with automatic shutoff. Good control includes multiple level switched control for different day and night light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.7.3 Small General Retail or Grocery

This design is typical of a hardware store, grocery store, shoe store and many other basic store types. Its walls are lined with shelf displays, and there are numerous freestanding displays in the center of the space. A point-of-sale is the middle of the store.

The design uses 2 ft x 2 ft general lighting luminaires and F40T5 twin tube wall-washers. The 2 ft x 2 ft luminaires could be lensed, parabolic, or recessed “indirect” with relatively similar results. Each luminaire employs approximately 50 watts of lamp and ballast: three 17-watt T-8 lamps (47 W at BF=0.99), two F31 or F32T8U lamps (50 W at BF=0.78) or a single 50-watt F40T5 twin tube (51 W at BF=1.0) would be workable sources depending on the luminaire. The store window area is highlighted with 37-watt MR-16 IR accent lights. Daylighting enters through the storefront only. The connected power for this design is 1.90 W/ft².

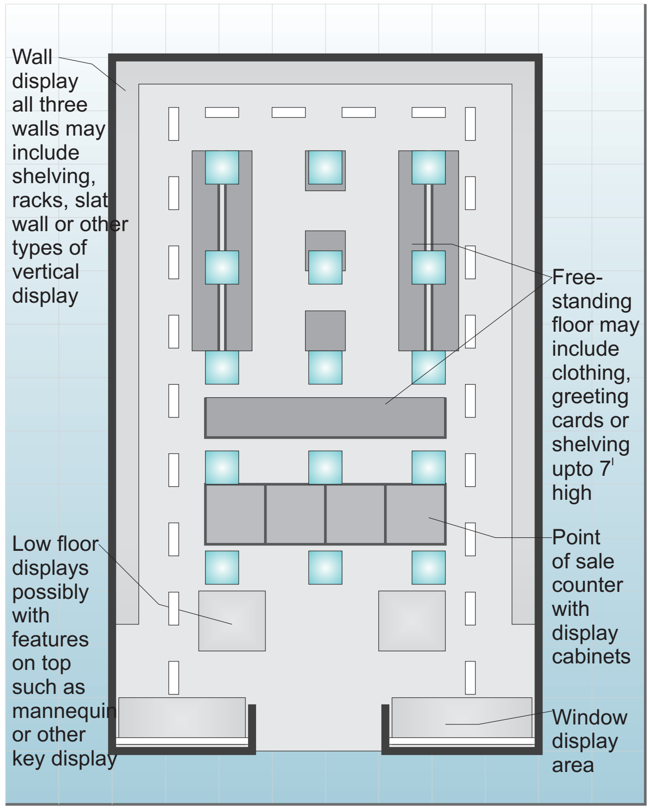


Figure 5-21 – Lighting Application, Small General Retail or Grocery
Electric lighting: 2 ft x 2 ft recessed luminaires with (3) F17T8 lamps; perimeter wall-wash using F40T5 twin tubes and .85 BF ballasts; (4) 37 W MR-16 accent lights in the window. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different day and night light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.8 Classrooms

The typical K-12 classroom is 960 ft² and measures 30 ft x 32 ft. Two electric lighting examples are provided in this section. In addition, a daylighting example is developed for a 24 ft by 36 ft classroom. This size is typical of relocatable classrooms used by many school districts. Modern energy codes limit the lighting for classrooms to about 1.5 W/ft².

Controls

Occupancy sensors should be used with classrooms as the basic on/off mechanism, preferably in conjunction with manual override switches that permit intentional darkening of portions of the classroom. Energy savings range from 5–15% in elementary schools to as much as 30% in colleges, presumably due to the diversity of use and schedule.

When used in classrooms with good daylighting design, automatic daylighting controls can save profound amounts of on-peak energy. Estimates range from 20–60% depending on location, solar orientation, season and weather. Classrooms operating in the summer during peak electric load situations should be especially designed to take advantage of daylighting.

5.8.2 Classroom, Suspended Luminaire

Pendant mounted luminaires are highly recommended for classrooms because they provide uniform, glare-free illumination. This example illustrates the use of a modern suspended direct-indirect or semi-indirect luminaire. Luminaire light distribution can vary from 50% up/50% down to 10% up/90% down, depending on design choice. The luminaires use two T-8 lamps. A higher percentage of uplight ensures comfortable light; a higher percentage of downlight increases efficiency.

With normal light output electronic ballasts, this design produces at least 50 footcandles at 1.16 W/ft². Some may wish to add a chalkboard light to the design, separately switched, which increases the lighting power by about 0.13 W/ft². Manual access to dimming would dramatically increase the flexibility of either classroom design for audio/video and computer work.

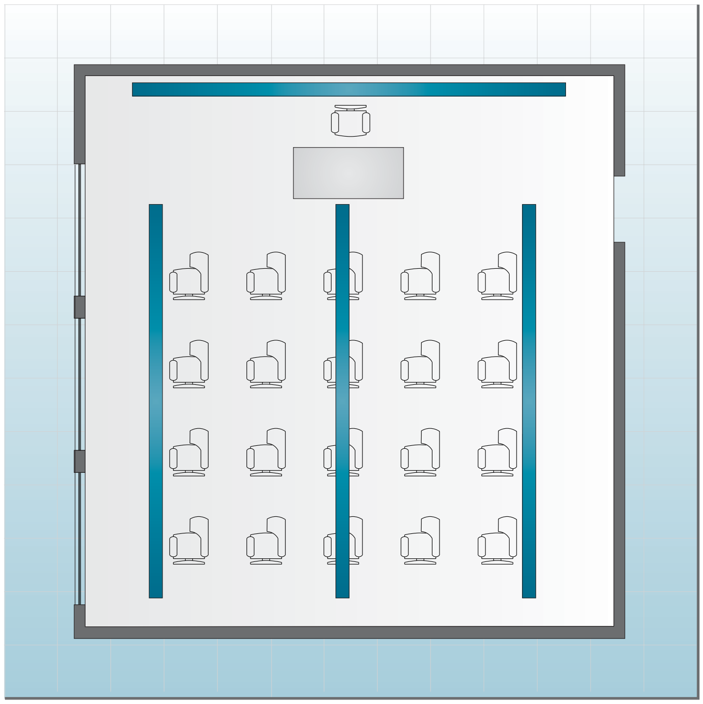


Figure 5-22 – Lighting Application, Classroom, Suspended Luminaire

Electric lighting: Two-lamp T-8 direct-indirect or semi-indirect luminaires and normal ballast factor ballasts. Optional: chalkboard lighting using (4) F32T8 or F28T5 lamps. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with daylighting, adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.8.3 Classroom, "Donut" Layout

This example illustrates a classic but effective low-cost lighting layout, the “donut.” Long preferred by school architects and engineers, the donut employs low-cost lens troffers to achieve good vertical surface illumination on all walls. Very high light levels, well over 70 footcandles, are produced at 1.29 W/ft² using two-lamp T-8 luminaires and low ballast factor electronic ballasts. Depending on the ceiling grid, it may be possible to reduce luminaire quantity into an attractive pattern; with 20 luminaires, the connected power drops to 1.08 W/ft².

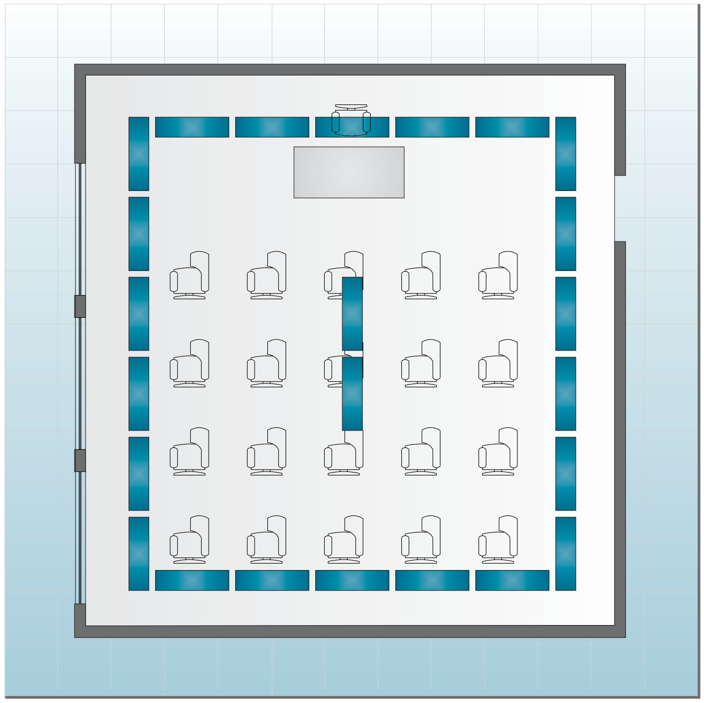


Figure 5-23 – Lighting Application, Classroom, "Donut" Layout

Electric lighting: "Donut" layout with two-lamp T-8 troffers and low ballast factor ballasts or normal light output ballasts and automatic daylighting controls. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with daylighting, adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

5.8.4 Classroom, Daylighting Example

In this example, a smaller classroom measuring 24 ft x 36 ft is used (see Figure 5-24). This is about the size of pre-fabricated relocatable classrooms, which are common in many school districts. The model has windows all along the long west wall, which is a poor solar orientation.

The electric lighting system consists of two rows of suspended luminaires, each with two F32T8 lamps. Controls are provided so that the luminaires near the window can be switched or dimmed separately from those away from the window.

A primary design challenge with daylighting is to maintain uniform lighting throughout the space. Figure 5-29 through Figure 5-31 shows the illumination in the space for various daylighting and night conditions.

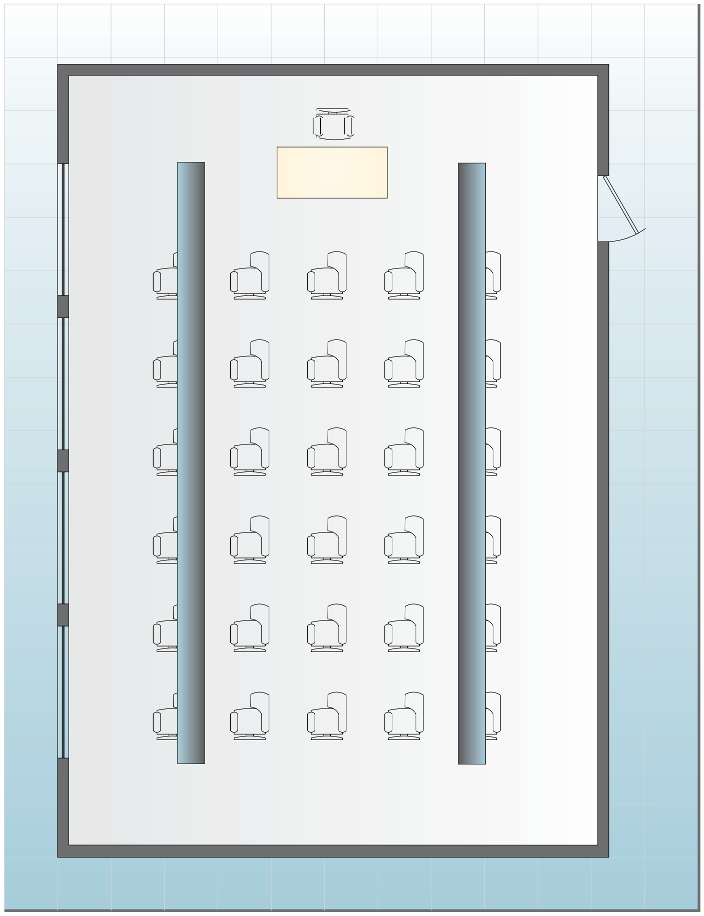


Figure 5-24 – Lighting Application, Classroom, Daylighting Example

The lighting system in this 24 ft by 36 ft classroom consists of two rows of indirect luminaires, each with two F32T8.lamps. Minimal control includes basic switching with automatic shutoff. Good control includes multiple level switched control for different light levels. Optimal control includes dimming for all fluorescent and compact fluorescent luminaires, with daylighting, adaptive compensation and peak demand limiting. (See Table 5-1 for controls rating scale.)

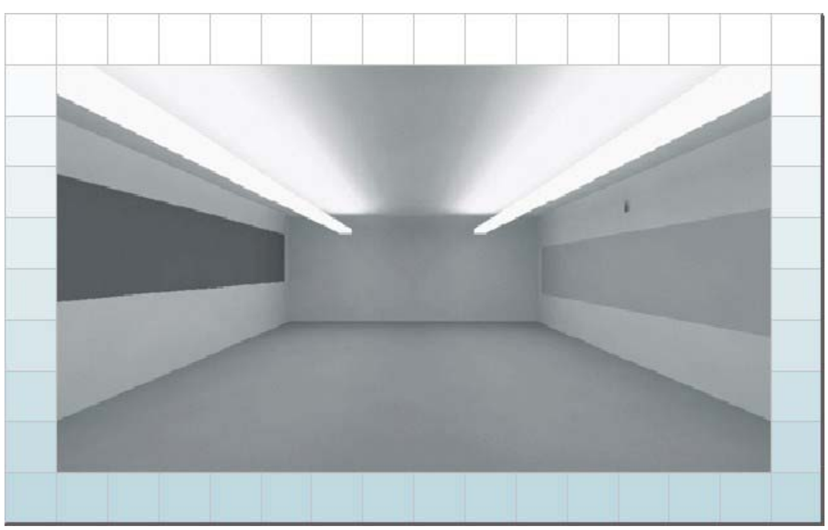


Figure 5-25 – Gray-scale Rendering, Electric Lighting Only

At night and on early winter mornings, the classroom is evenly lighted by suspended direct-indirect luminaires. This modern lighting system provides a minimal of 40 fc (400 lux) and an average of 50 fc (500 lux) over the desk area at 0.96 W/ft²(1.11 W/ft² with chalkboard light).

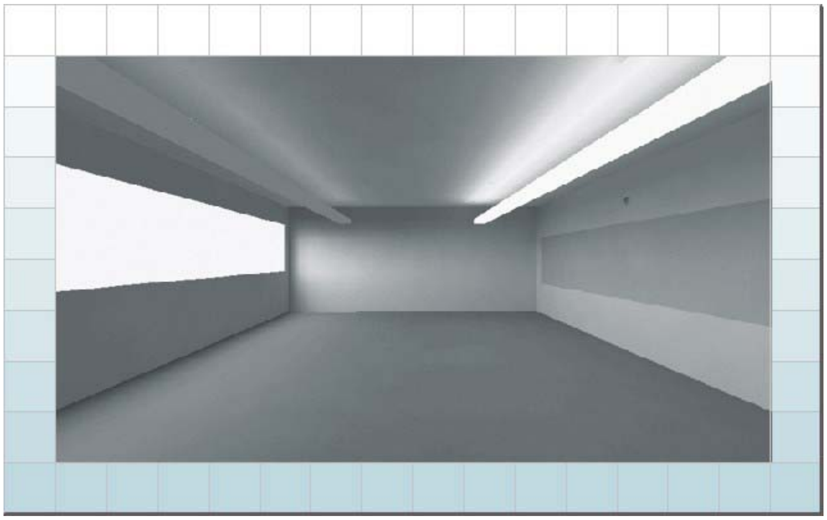


Figure 5-26 – Gray-scale Rendering, Typical Days

Many days of the year, some natural light enters through glazing having 50% visible light transmission and low emissivity ("low-e"). This permits the lights near the windows to be dimmed to 5%. The lights near the inner wall operate between 50% and 100% light output. The connected power is about 0.6 W/ft², but light levels are over 60 fc (600 lux) for most of the room.

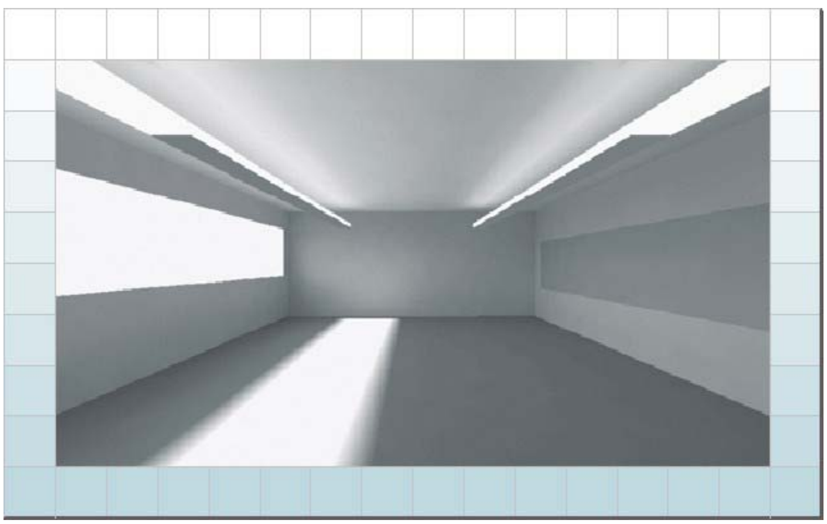


Figure 5-27 – Gray-scale Rendering, Sunny Days, Direct Sun

On sunny days in the afternoon, direct sun can enter the room. It creates an average illumination level in the room, creating extreme brightness and contrast The average illumination in the room reaches 600–700 footcandles, and the hot spots exceed 2500 footcandles. This much daylight is the equivalent of 5 W/ft² of electric lights. In HVAC terms, this daylight is the equivalent of 5–6 W/ft² of electric lighting, even though the windows are high performance, low emissivity glazing with visible light transmission of 50% and a shading coefficient of 31%. This situation needs to be prevented.

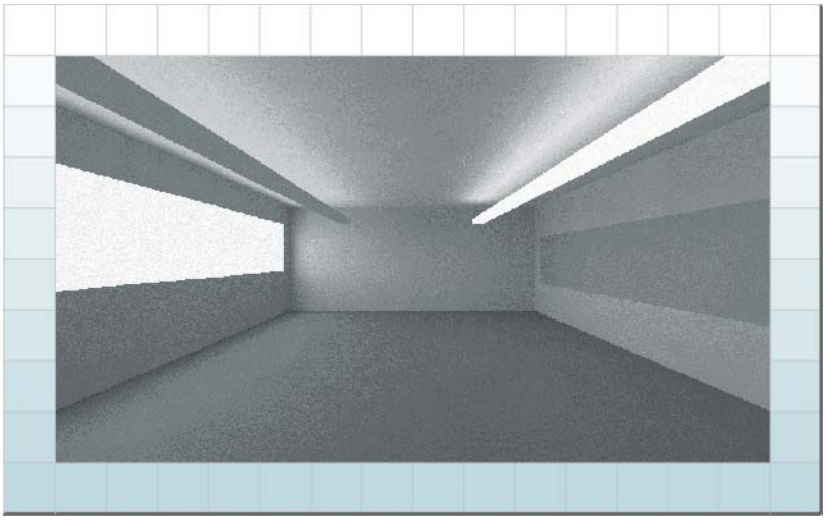


Figure 5-28 – Gray-scale Rendering, Sunny Days with Shading
Applying manually (or automatically) controlled shades with 5% diffuse transmission, the light levels return to usable amounts. Interior light levels reach a maximum of about 150 footcandles at peak solar load. The electric lights at the windows are turned off, and the interior row operates at 30% power. The chalkboard light, if used, is extinguished. Actual lighting power is 0.21 W/ft².

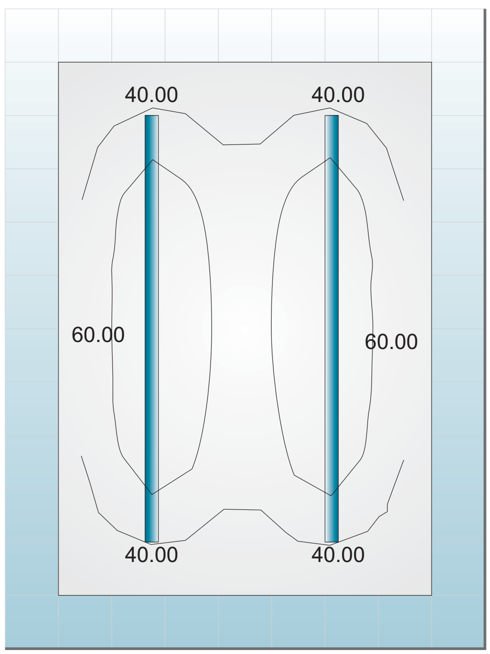


Figure 5-29 – Isolux Diagram, Electric Lighting Only
This isocandle plot shows the illumination pattern of the general lighting system at night or other times when the windows are disabled. Under the luminaires, the light level is 60 fc or better. Throughout the working area of the room, the illumination level is 40 fc or better. All of the room is at least 25 fc in the task plane. This efficient design operates at 0.96 W/ft² at full light output in this classroom.

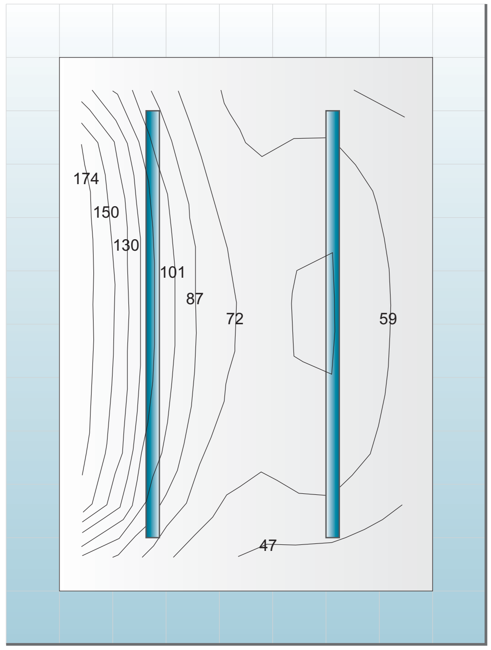


Figure 5-30 – Isolux Diagram, Typical Days

This isolux plot shows the high illumination levels near the windows, but also shows that light levels throughout the room are no less than about 40 fc and as high as 200 fc. To achieve this reasonable balance, the electric lights near the windows are dimmed to 5% light output but the lights towards the interior are operated at full light output. The result is a lighting system in which the average lighting power density most of the time is 0.50 W/ft² or less.

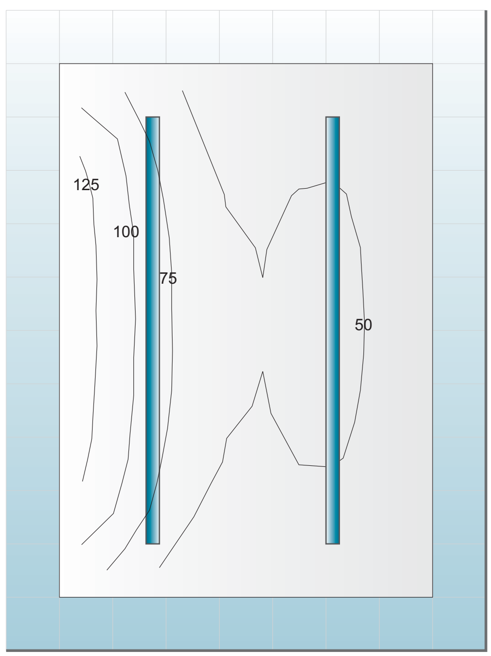


Figure 5-31 – Isolux Diagram, Sunny Days with Shading

The light levels are similar to the typical day in gradient and distribution. However, there is so much solar light even with 5% transmission blinds that the electric lights can be dimmed to 5% (exterior row) and 30% (interior row). The result is an average lighting power density of only about 0.22 W/ft² during direct sunny periods.

5.9 Exterior – Gas Stations

The design of modern gas stations, which often include a convenience store and other services, usually includes a canopy over the pump area. An unfortunate trend in the industry is to utilize drop-lens metal halide luminaires on the underside of the canopy that create substantial light trespass and contribute to light pollution. The glare from these luminaires, because of the lack of shielding, can contribute to vision impairment of drivers on adjacent roads.

IESNA recommends 20 footcandles for the pump area, but the actual value should be chosen in consideration of the setting. Half this value—10 footcandles—will work well in rural settings. Yet too often, light levels of 50–100 footcandles are used. Note that the IESNA recommendation for the approach ramp and driveway is only 2.5 footcandles. Extremely high light levels are not justified, except perhaps for inner city stations where security is tantamount.

5.9.1 Gas Station Canopy

The design shown here employs 2 ft x 2 ft wet label, recessed flat lens downlights. Recessed mounting depth is shallow, less than 8 in. Recessed lighting virtually eliminates light trespass.

This design can produce 15–20 fc maintained utilizing any of the following light sources:

- 100-watt metal halide with -20°F electronic ballast (110 watts each)
- 100-watt metal halide with -20°F magnetic ballast (123 watts each)
- (2) F40T5 twin tube compact fluorescent with 1.0 ballast factor and 0°F electronic ballast (80 watts total)

The compact fluorescent design has several advantages over the metal halide solution. It saves quite a bit of power, provides redundancy if a parallel circuit ballast is used, and takes advantage of the superior lumen maintenance of the compact fluorescent to provide equal maintained light levels to the metal halide. The fluorescent lamps last longer (20,000 hours versus 8500–10,000 hours for metal halide) and generally have superior color to the metal halides, especially the lower-cost lamps that will doubtless end up in this application. And the fluorescent lamps lend themselves far better to emergency lighting.

Unless starting temperatures under 0°F are needed, the fluorescent system is the more energy efficient choice. Lamp lumen depreciation (LLD) of the fluorescent is only about 90% at 6000 hours; the LLD of the metal halide is 70% at 6000 hours.

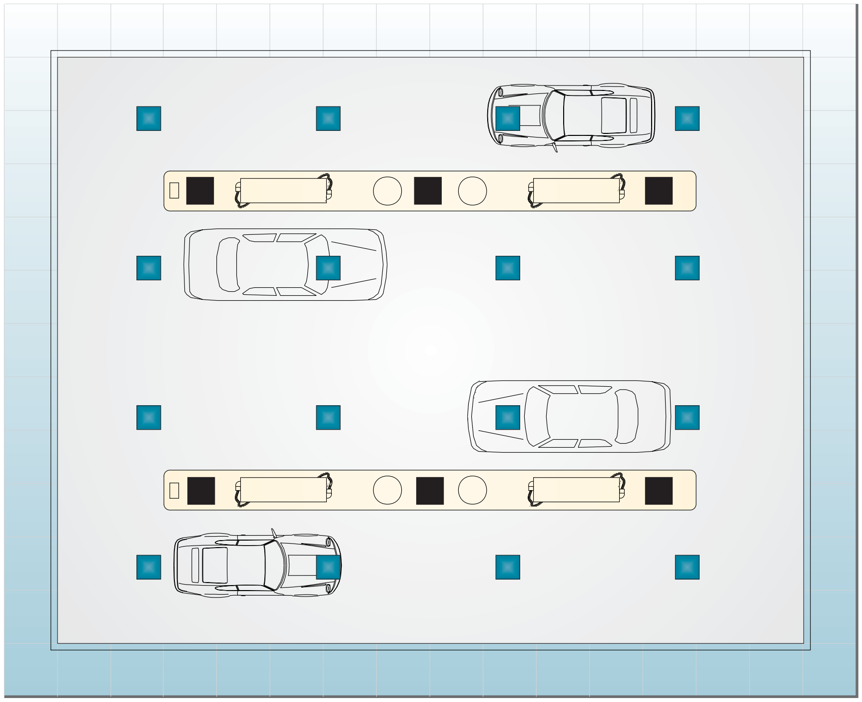


Figure 5-32 – Lighting Application, Gas Station
A grid of 16 recessed luminaires provide uniform illumination and minimal light trespass using either a 100 W metal halide lamp or (2) F40T5 twin tubes.

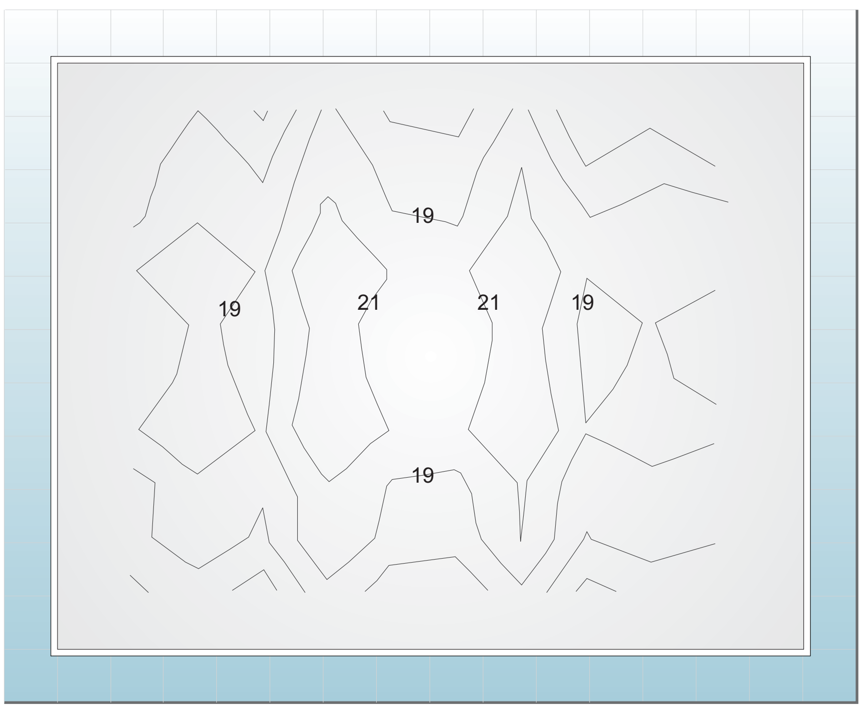


Figure 5-33 – Isolux Diagram, Gas Station
The design provides between 18 and 21 footcandles of illumination in a very even pattern.

6. LIGHT SOURCES AND BALLAST SYSTEMS

This chapter covers the technical and application aspects of electric light sources and natural daylight as used for general and task lighting in commercial and industrial applications. Information on ballasts and other equipment necessary for the proper operation of the light source is also included. The emphasis is on the practical information necessary to properly analyze, choose, specify, install and maintain light sources for optimum energy use and performance.

Historically, there has been a tendency not only to think of electric lighting and daylighting separately, but also to focus on one to the neglect of the other. Although there is little information currently available about the performance of combination daylight and electric lighting systems, such systems exist. Many have been found capable of providing excellent quality lighting as well as significant energy savings. A goal of the *Advanced Lighting Guidelines*, therefore, is to expand the information base in such a way that daylight will be routinely considered in the same way as electric sources.

Figure 6-1 –Various Light Sources for General Lighting

Energy-efficient lighting starts with the light source and the transformation of electrical energy into visible energy: light. No single type of lamp is optimum for all situations. Consider the numerous choices carefully. Just a few of the available halogen incandescent, fluorescent and high-intensity discharge lamps are pictured here. Photo courtesy OSRAM SYLVANIA.

In addition to considering daylight as a light source, this chapter discusses the following energy-efficient electric light sources:

- Tungsten-halogen and other high performance incandescent lamps
- Fluorescent lamps and their ballasts, including compact fluorescent lamps and electrodeless or induction lamps
- High-intensity discharge (HID) lamps and their ballasts focusing on metal halide, high-pressure sodium, and low-pressure sodium lamps
- Light-emitting diodes (LEDs)

Mercury, general service incandescent and some older fluorescent lamps such as the once-dominant 4-ft F40T12 are considered obsolete for the purposes of these *Advanced Lighting Guidelines* and will be discussed only briefly for comparison or reference.

6.1 Energy-efficient Lamps

The electric light source is the point in a lighting installation where electricity becomes visible light. Electric energy, a quantity that can be measured, tracked and analyzed, becomes, at this point, something much less precise. It turns into "visually evaluated radiant energy" that is sensitive to the physiological, subjective and emotional interpretations of human beings (refer to chapter 2 for more about lighting and human performance). From an energy standpoint, however, the light source is the point where lighting energy efficiency begins. The figure of merit, lumens per watt (lm/W), is the light that results per unit of electrical power. Using an efficient or, more properly, *efficacious* source sets the stage for an efficient lighting system. Choosing a light source is therefore a key decision since even the best luminaires or application ideas cannot typically make up for a poor electricity-to-light conversion process.

Energy-efficient lighting also implies a time factor. Just as electric energy is power x time, luminous energy is lumens x time (usually expressed as lumen-hours). Flash photography, for example, is always thousands of times more energy efficient than photography using photo-floodlighting. This is not because of any inherent efficacy difference among the light sources used, but because of the time each light source is on, typically microseconds versus minutes or even hours.

From a lighting point of view, the key performance characteristic of a light source is usually its light output or lumen rating. However, depending on the application, knowledge of other lamp performance factors may also be crucial to achieving energy-efficient lighting. In a display application, for example, knowing the lumen output of a reflector lamp is helpful in determining if the lamp is powerful enough for the job. But to actually calculate the illumination (and the required watts to do the job) on an object in the display, the intensity distribution (candlepower) of the lamp must also be known. Energy-efficient lighting, therefore, implies consideration of the lamp within the context of the whole lighting system over time.

6.2 General Performance Characteristics

The following pages of this section discuss general performance characteristics of energy-efficient light sources. For performance characteristics and application information for specific types of light sources, refer to sections 6.3 through 6.8. For information about performance characteristics of luminaires, see chapter 7.

6.2.1 Efficacy and Energy

The process of transforming electrical power into visible light is different for every major light source. As indicated in the chart below, discharge lamps are substantially more efficient than incandescent filaments, but every light source generates significant heat as an unwanted byproduct of the conversion process. The efficacy figure of merit, lumens per watt, takes all such losses into account as well as accounting for the varying spectral output of the lamp. "System efficacy" is measured for lamp/ballast combinations as lumens/ballast input watt since the ballast is essential to the lamp's operation. Figure 6-2 compares system efficacy for a number of light sources for general lighting.

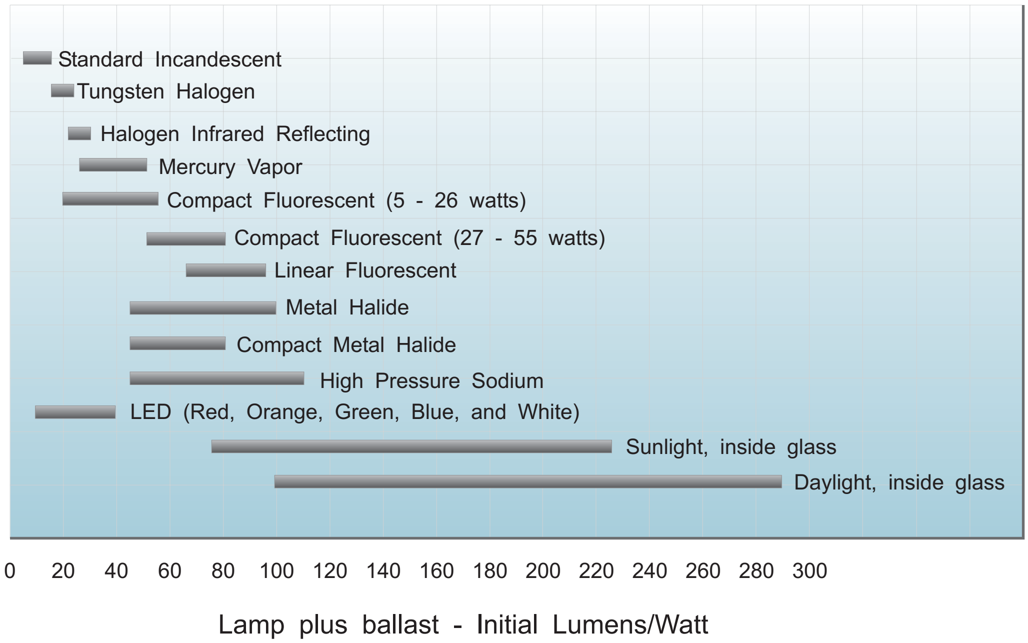


Figure 6-2 – Efficacy Comparison of Light Sources for General Lighting
Ballast watts included for discharge lamps systems. Sunlight and daylight ranges calculated inside *of single pane clear glass and high performance glass.*

As lamps burn, system efficacy typically decreases due to the loss of lamp light output. System power remains relatively constant. Low-pressure sodium (LPS) systems are an exception. With these, lamp light output is relatively constant, but the lamps draw increasing power over time. Tungsten-halogen lamps are unique in that efficacy is constant, within a few percent, over the life of the lamp.

6.2.2 Lamp Life

The life of a lamp is typically quoted as a single value. In reality, it's one point on a statistical function. The single value is the number of hours a group of lamps can be expected to operate before 50% have failed. Some lamps will fail earlier and some will fail later than rated life, so it's not possible to predict when an individual lamp will fail. Rather, for each lamp, there is a probability of failure at various times.

Mortality Curves

Lamp mortality curves graphically describe the statistics of lamp failures over time. Since lamps are typically manufactured in large quantities, their failures usually follow a statistically normal distribution. Mortality curves are the cumulative representation of that distribution and indicate the percent of operational lamps as a function of time. Written warranties from lamp manufacturers for their products include mortality curves—or numerical descriptions of those curves—over the hours of warranty coverage.

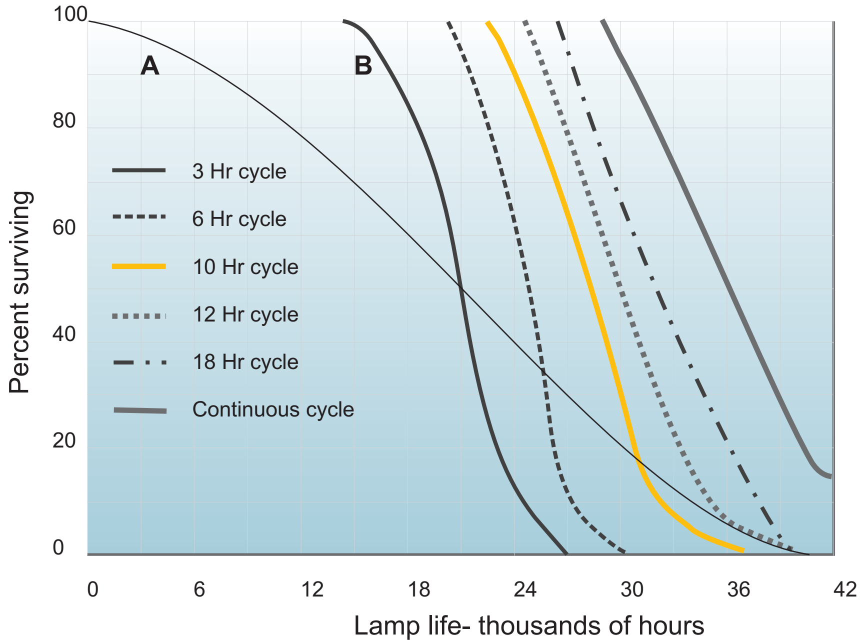


Figure 6-3 – Lamp Mortality Curve Examples

These lamp mortality curve examples indicate how lamp life can vary as a function of burning cycle and lamp design.

A careful analysis of a lamp mortality curve can indicate how confident the lamp manufacturer is of the lamp's performance. Lamp designs that have been manufactured for some time and for which the manufacturer has gathered substantial life data are relatively "flat" (that is, they show few failures) over the first 50–80% of life. Then toward the rated life point, the number of failures increases rapidly (Figure 6-3, curve B). The mortality data of newer or less reliable lamp designs (Figure 6-3, curve A) will indicate more failures early in life with substantial failures also occurring well beyond the rated life point. Note that lamps "A" and "B" both have the same rated life of 20,000 hours. These comparison curves are for a 3 hour operation time per start. The other mortality curves shown in Figure 6-3 are for lamp "B", but with different operating time per start.

Life vs. Hours/Start Ratings

Starting has little effect on incandescent lamp life, but can dramatically affect the life of discharge lamps due to degradation of the lamp cathodes. The damage to the cathodes during each start is equivalent to many hours of normal operation. Multipliers or curves provided by the manufacturer (Figure 6-3) permit estimating lamp life for other hours/start values.

Alternative Definitions of Lamp Life

Other definitions of lamp life may be appropriate depending on the application. For example, newer electrodeless fluorescent lamps don't fail due to cathode deterioration, so lamp life is estimated based upon other components of the system.

Lamps may also effectively be at end-of-life when:

- the lamp light output drops below a given value (useful life);
- color shift occurs so that the lamp is no longer usable in the application;
- lamp efficacy falls below the value at which it's economical to continue to operate the lamp (economic life);

- the lamp starts to cycle (goes through a process of starting, warm-up, drop-out, cool down and then starting again). This definition particularly applies to standard high-pressure sodium lamps (HPS);
- the lamp becomes unstable (applies generally to discharge lamps); or
- statistically, the probability of lamp failure increases to a certain value (used to determine group replacement intervals).

6.2.3 Maintenance of Light Output

The lamp lumen depreciation (LLD) curve is significant data from an energy standpoint because it describes how the source's light output (and efficacy) changes over time. A 400-watt metal halide lamp rated for 36,000 lumens (90 lm/W) initially appears to be an efficacious choice. But if the mean lumen rating of the lamp is 24,000 lumens, then over the time it will be using energy, it's only a 60 lm/W lamp and should be evaluated accordingly. Perhaps the most efficient way to use such a lamp is to replace it before rated life to avoid the hours of operation and energy use at minimum efficacy.

Lumen Maintenance Curves

For discharge lamps, and particularly fluorescent types, depreciation is very rapid during the first 100 hours or so of burning and thus manufacturer's ratings are, by industry consensus, established after that period of time.

Plots of light output versus time for lamps, known as lamp lumen depreciation (LLD) or lumen maintenance curves, are published by lamp manufacturers. Points on these curves, usually the mean and LLD values, may be published as part of the lamp's specification data. The mean and LLD points can vary for different lamp groups, but for fluorescent lamps they are typically given at 40% of rated life and 70% of rated life (in hours) respectively due to the shape of the depreciation curves. Figure 6-4 shows lumen maintenance curves for best current technology T-8 fluorescent and metal halide systems.

Use care in evaluating depreciation data. As the transition to electronic ballasts for HID and fluorescent lighting continues, manufacturers are changing the way they are reporting lamp depreciation. Manufacturers realize, of course, that higher LLD values go right to the "bottom line" and directly affect the initial number of lamps and luminaires as well as the project's initial cost. They may show, for example, only optimized depreciation data that may apply to just certain lamp/ballast combinations. Check that the data apply to the ballast types, lamp types and hours/start cycles being evaluated.

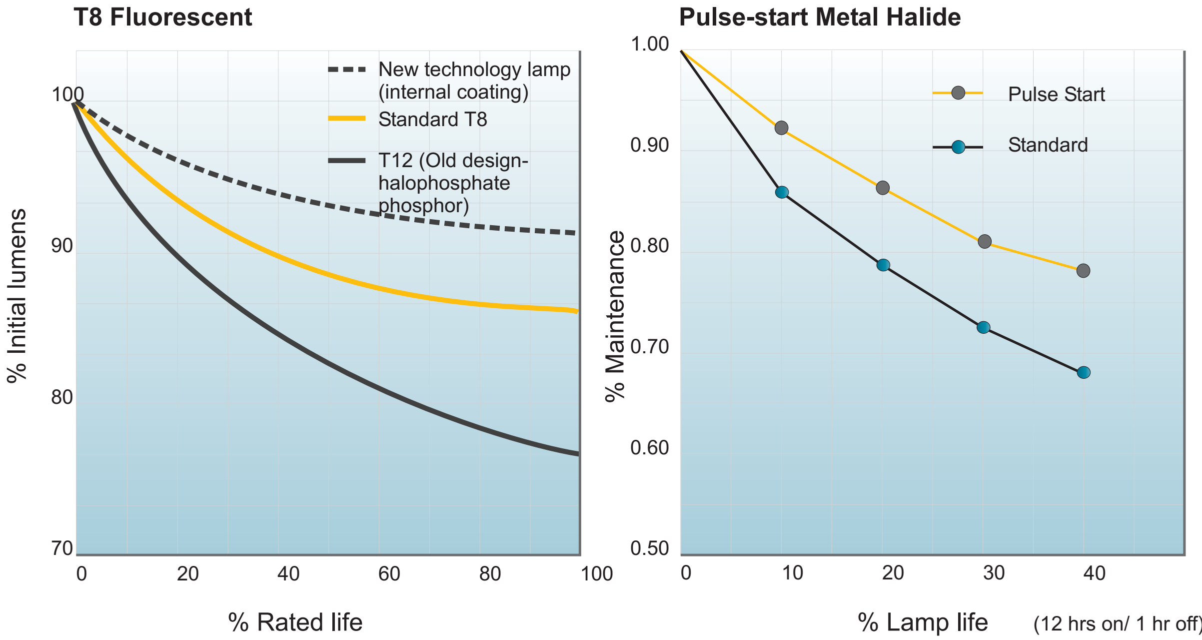


Figure 6-4 – Lumen Maintenance Curves

Shown for best current technology T-8 fluorescent and metal halide systems.

6.2.4 Color

The two metrics used to specify light source color are chromaticity or correlated color temperature (CCT), and color rendering index (CRI). These quantities describe, respectively, the color appearance of the light source and the color appearance of the objects being lighted. Both are defined according to international standards and are applied by manufacturers to light sources worldwide. For design guidance related to color appearance, refer to section 4.3.

Chromaticity

Chromaticity can be expressed in two ways: as "x-y" coordinates on the International Commission on Illumination's (CIE) chromaticity diagram (Figure 6-5) or as CCT in Kelvin (K). The CIE diagram (if viewed in color) is particularly descriptive because it provides both a sense of the visual appearance of the light sources and an indication of how visually "warm," "cool" or tinted a space lighted with the source will appear. The "black body locus" shown in Figure 6-5 traces the chromaticity values of sunshine and natural daylight as they vary by season, weather or time. It also traces tungsten filaments, iron bars and other "black bodies" as they are heated to the actual temperatures (in Kelvin) indicated. The rectangle on the locus in the figure defines the usual range of incandescent/halogen filament temperatures of lamps used for general lighting. Here the term "color temperature," used historically to describe incandescent lamp chromaticity, correctly applies.

Note that most general lighting sources have CCTs that lie on or close to the locus. This is a deliberate decision on the part of lamp engineers to make such widely used lamps appear more “natural." The advent of rare-earth (RE) fluorescent phosphors made possible efficient "warm" colors for the first time, so preferred CCT values (based on manufacturer's North American lamp shipments) have gradually moved from 4100K (the classic "cool white" color) to 3500K for commercial interior lighting.

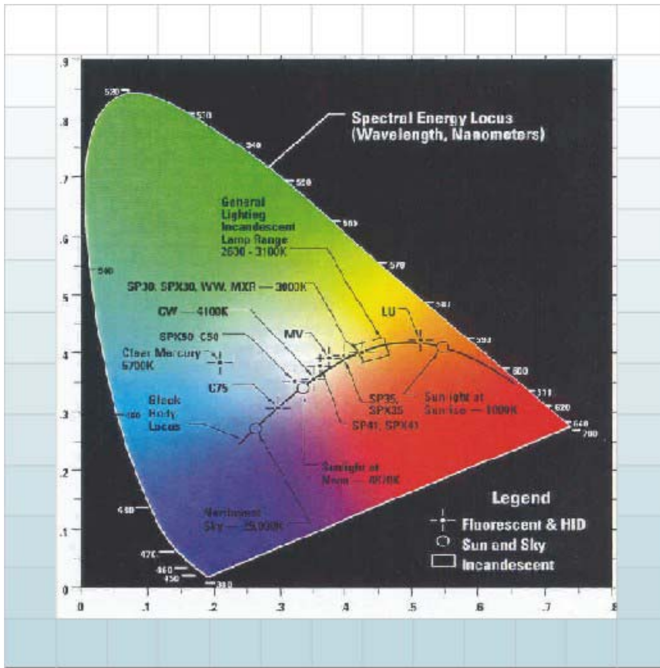


Figure 6-5 – CIE Chromaticity Diagram

Marked with the color points of general lighting lamps. Graphic courtesy GE Lighting.

Lamp Color Mixing

CCT values for mixtures of lamps can be estimated by plotting the x-y values of each light source on the diagram. If two sources are involved, the resulting CCT will fall on a line drawn between the two points. If the light from three or more sources is mixed, then the area encompassed by the perimeter lines connecting the CCT values for the sources defines the range of CCTs that can be achieved. Determining the exact CCT point along the line or in the defined region requires a calculation and knowing the amount of light coming from each source. "White" light can be achieved (if that is the objective) by combining various sources of remarkably different colors. This technique is useful when both color and efficacy must be optimized, such as when sources of varying efficacies are combined or when colored lamps are used to make white light. Some light-emitting diode (LED) lamp arrays, for example, use this technique.

Color Rendering

The color rendering index (CRI) is a fairly good indicator of a lamp's ability to make the color of people and things appear as expected. It's determined by calculating how a particular light source makes things appear compared to a reference or "ideal" source of the same CCT. The reference sources are incandescent lamps or outdoor daylight. Considering that the CRI must take into account the variables of human vision and psychology (see chapter 2), it works well. But CRI should be used as an indicator for light source comparisons rather than a precision tool for the absolute rating of a light source's color characteristics.

The most efficient fluorescent and HID sources have traditionally been characterized by moderate to poor color rendering. For example, cool white fluorescent sources have a CRI of 62; standard metal halide, 65–79; high-pressure sodium, 22; and low-pressure sodium, 0. New technology light sources can now avoid the traditional efficacy versus color trade-off, as well as provide higher CRIs and a choice of CCTs. The typical CRI range for fluorescent lamps is now 70–90 and for metal halide it is 65–85. Compact fluorescent lamps are typically rated at 82–85.

Figure 6-6 illustrates the range of choices available in energy-efficient lamps considering both CRI and CCT. Lamps around the 3500K value are widely used currently for commercial and industrial interior lighting systems.

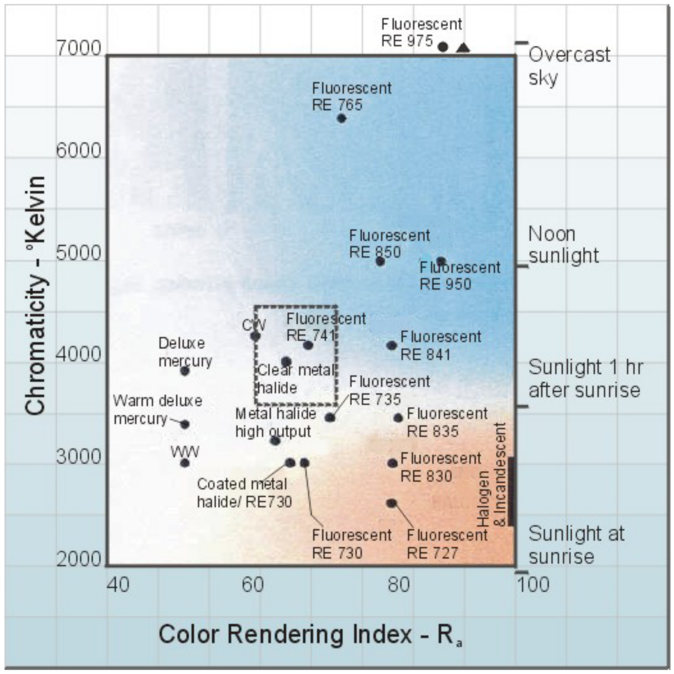


Figure 6-6 – Chromaticity & Color Rendering Index for a Variety of Fluorescent and HID Lamps
Box shows range of conventional and pulse start metal halide. Graphic courtesy GE Lighting.

Efficient Lighting and Color

The color characteristics of a light source is one of many factors that must be evaluated to choose the best source for a particular application (see section 4.1 for a discussion of lighting design criteria). Usually, the CCT of a light source is chosen first to match the desired atmosphere of a space; then the lamp with the highest CRI in the desired CCT range is selected. There are, however, some cautions:

- Numerical comparisons of CRI are meaningless unless the sources involved have similar CCTs.
- The eye cannot typically see differences of 3–5 in CRI values.
- The CRI system is most accurate in the range of 80–100.
- Lamp color is sometimes linked to vision, glare, productivity or health benefits. While some lighting research indicates that the use of high CCT sources may enhance visual acuity under certain conditions, how this applies to lighting practice is still controversial. See sections 2.1.7 and 4.2.2 for further discussion.
- Lamp color, and especially CCT values, in full-scale applications are modified by luminaire characteristics, room shape, room surface colors, reflectances, illumination level and the presence of daylight (refer to section 4.1 for more about lighting design criteria). The best design practice is to visually evaluate a lamp color together with the colors used in the application.
- Side-by-side color comparisons using different lamps are useful, but human eyes adapt to color and so the final choice should be made after adaptation under the source or source combination proposed for the application.

Lamp Color Selection Guidelines—General Lighting

- First, think about the overall color atmosphere of the space. Should it be visually "warm" (2700K–3000K), "neutral" (3500K) or "cool" (4000K or higher)? Office spaces, for example, have traditionally been lighted with 4100K fluorescent lamps; but 3500K lamps are now widely used and private or small offices may be designed to have a "residential" look that is enhanced with warm-toned lamps. In general, 3000K or 3500K fluorescent lamps match MR and other halogen incandescent lamps while 2900K fluorescent lamps match standard A-line and other household-type incandescent lamps.
- Second, pick a lamp with a color rendering index (CRI) appropriate for the application. Remember, colors will look more vivid—more natural and normal—with high-CRI lamps; the "reference" light sources for most people are outdoor daylight (CRI = 100) or standard incandescent lamps (CRI = 98–99). So usually, "the higher the CRI, the better." CRIs of 65–70 (minimum) are available using high-efficiency metal halide or fluorescent lamps; these are suitable for many commercial and industrial situations. Better yet are lamps with CRIs of 80 and above, but there may be added cost. In commercial lighting situations where color appearance is of some importance, lighting with CRIs of 50 or less is generally not acceptable.
- A mock-up or actually seeing room colors with the lamp or lamps being proposed is an invaluable experience. Because people may perceive color differently, lamp color selection—as with fabric or paint color selection—is a subjective process.
- If fluorescent table or task lamps are used, match the color of the lamp used for general lighting with the color of the task lamp. This avoids odd-looking color patterns in rooms.

6.2.5 Lamp Temperature Characteristics

Electric lamps are designed to operate over the range of temperatures usually encountered by people. But with the major exceptions of fluorescent lamps and LEDs, electric lamps are not particularly sensitive to ambient temperatures. Fluorescent lamp light output and efficacy, however, do depend on the temperature—and, specifically, the coldest point—of the tube or bulb wall, and function generally as indicated in Figure 6-7. Below the optimum temperature point, which varies according to the lamp design, fluorescent lamps become increasingly inefficient. Starting the lamp is also more difficult at low temperatures beginning at about 10°C (50°F), and ballasts should be rated accordingly. Fluorescent lamps, however, can be applied in environments with temperatures as low as -29°C (-20° F) with the proper lamp, ballast and luminaire.

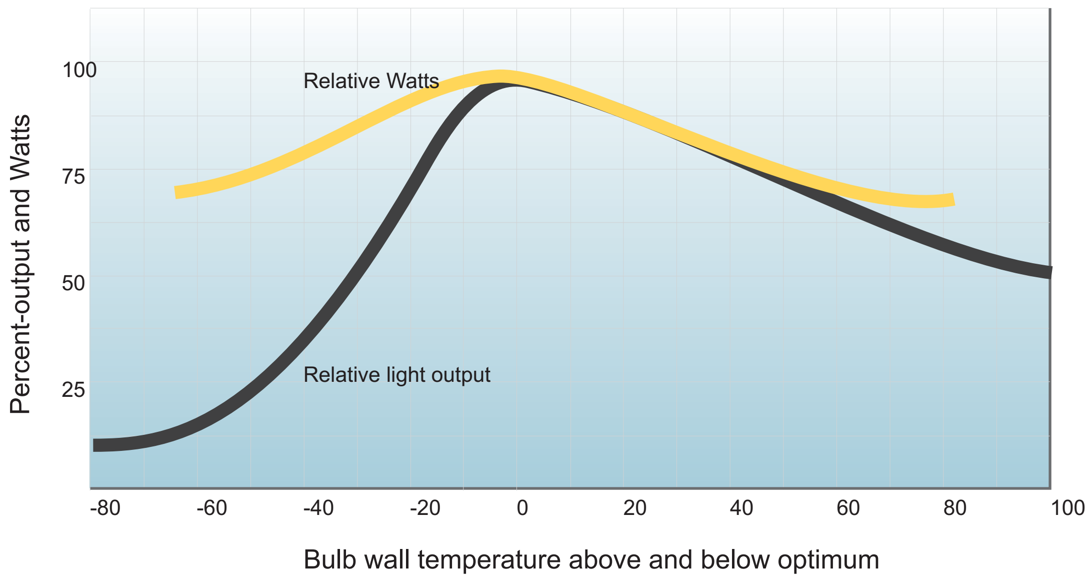


Figure 6-7 – Fluorescent Lamp Temperature Characteristics

Light output and wattage of fluorescent lamps vary as bulb wall temperature varies from the optimum of 100°F. Lamps become increasingly inefficient if operated below their design temperatures.

For luminaire types in specific retrofit installations, Ballast Factor and Thermal Factor can be combined into an Application Correction Factor (see section 7.9.3),

6.2.6 Burning Position Considerations

Some types of lamps are designed to be burned only in specific positions. Linear double-ended tungsten-halogen lamps, for example, must be burned within a few degrees of horizontal or the lamps will quickly blacken and fail due to the resulting non-uniform distribution of halogen gas. (See section 6.4 for a thorough discussion of high-performance tungsten-halogen lamps.)

Metal halide lamps, as a group, are subject to the greatest number of burning position considerations since optimum lamp performance, including light output, lumen maintenance, lamp life and color, depend on a uniform distribution of molten halides within the arc tube and that distribution changes with burning position.

Light output values for universal-burn metal halide lamps operated horizontally can be reduced by 10% and lamp life by 25% compared to lamps operated vertically. For optimal performance, match the lamp to its burning position in the intended luminaire and, unless other information is provided, choose luminaires that burn the arc tube vertically. (Section 6.6.2 discusses metal halide lamps in detail.)

6.2.7 Discharge Lamp Ballasts

Ballast Developments

High-frequency electronic ballasts are now in common use thanks to the development of high-efficacy T-8 fluorescent lamp/ballast systems over the last decade. For the same light output, fluorescent systems now use 30–40% less power compared to classic T-12 fluorescent lamps and electromagnetic ballasts of the 1970s and 1980s. In addition, their lamp life is the same or longer, and the maintenance of light output has improved by about 10%. Fluorescent system efficacy improvements are the result of lower ballast losses (about 50% less) and the fact that fluorescent lamps operate about 10% more efficaciously at high frequencies (10–50 kHz). HID lamps, unfortunately, are not more efficient when operated on high-frequency power; but electronic HID ballasts have lower losses and can improve system performance compared to electromagnetic units. Figure 6-8 shows some examples of electronic ballasts.

Advanced Technology Ballasts

New developments in fluorescent and HID ballast technology are focusing on improved system performance, control capability for dimming, daylighting integration, energy management functions, and solutions to some longstanding problems that can occur when lamps reach end-of-life.

The traditional functions of the ballast are starting the lamp and then operating the lamp within the electrical ratings specified by the lamp manufacturer over a defined range of input voltages and thermal conditions. Advanced ballast features now being built into products entering the market include:

- Circuits that automatically sense the input voltage so a single ballast type can be used on more than one voltage.
- Load circuits that sense the lamp type and are able to control several lamp wattages automatically.
- Multiple-lamp ballasts. For fluorescent systems, the traditional two lamps per ballast has now changed to three or four lamps per ballast. Advanced designs work efficiently with less than the maximum number of lamps connected.

These features reduce the number and type of ballasts that must be stocked, and potentially reduce replacement and wiring errors.

Additionally, advanced ballasts may include:

- *"Smart" circuitry* that times and regulates critical lamp starting and restarting processes. Ballasts with "starting scenarios"—especially in fluorescent systems—improve lamp lumen maintenance and can typically lengthen lamp life by 5000 to 10,000 hours for linear lamps. They are ideal for applications involving frequent switching, such as circuits controlled by occupancy sensors.
- *End-of-life sensing.* Some fluorescent and HID lamps do not fail simply by going out at normal end-of-life. HPS lamps cycle on and off, the arc tubes in metal halide lamps can shatter and some small-diameter fluorescent lamps may experience seal failures near the cathodes although non-passive failures of lamps are rare. End-of-life sensing circuitry is designed to constantly monitor the system and turn the lamp off as it reaches its failure point.
- *Dimming.* Step and continuous dimming are significantly less costly if they are part of an electronic ballast. Dimming ranges and performance have been extended in fluorescent systems. (See section 8.2 for a detailed discussion of dimming controls.)
- *Control.* Standardized photocells and linking circuitry are being built into standard ballasts so that control functions can be activated, changed as needed or easily added later. (Refer to chapter 8 for more information about controls.)

Figure 6-8 – Examples of Electronic Ballasts
Photos courtesy OSRAM SYLVANIA and Aromat.

6.3 Daylight

There are at least three reasons to consider daylighting in advanced lighting applications:

- People like it. Studies have indicated that people prefer daylit rooms to interiors dominated by electric lighting (U.K. Department of the Environment 1998).
- There is a substantial energy saving potential.
- Superior-performing daylighting/electric lighting systems are beginning to appear. The use of standardized systems rather than custom-built installations tends to reduce costs and enable comprehensive testing and evaluation.

6.3.1 Daylight as a Light Source

The light source characteristics of daylight range from direct sun, which acts as a powerful point, source to a cloud-covered sky dome, which supplies light as a large diffuse illuminator. Thus, it is useful to distinguish between *sunlight*, the intense direct beam light from the sun, and *daylight*, the more gentle diffuse light from the blue or clouds. For lighting design purposes, at least four sky conditions should be considered:

- Direct sun
- Clear blue sky
- Partly cloudy sky
- Overcast sky

The direction and intensity of sunlight is easily predicted, and the designer should be fully aware of how the angle of the sun and its luminous intensity vary by location, time of day and time of year. This information is readily available in standard reference books, and is also built into many computer programs with daylight modeling capability. The U.S. National Weather Service provides default information for over 200 locations in the United States based on its estimates of a "Typical Meteorological Year" or TMY2 data.[1] TMY2 data accounts not only for solar position, but also typical cloudiness patterns and diffuse scattering of light in the atmosphere. It provides illumination data per hour per day for direct beam illuminance (normal to the beam), horizontal diffuse illuminance, and global horizontal illuminance (horizontal beam plus diffuse).

The illuminance of a clear blue sky is a function of the position of the sun. The portion of the sky surrounding the sun will be brightest, and the sky areas opposite the sun will be darkest. Thus, when the sun is in the south, the sky dome will be brightest in the south and darkest to the north. Clouds behave in a similar fashion when they reflect the sun's light, being brightest directly opposite the sun. However, cloud cover can also diffuse the sun, and vary considerably in density and reflectivity.

The most variable condition is the partly cloudy sky. As the sun moves from behind clouds to clear sky, illuminance and sky luminance can change rapidly. Figure 6-9 illustrates the magnitude of variability for one partly cloudy day. Note the rapid shifts in illumination levels between noon and 2 PM as clouds pass by directly underneath the sun.

[1] Available at Web site: http://rredc.nrel.gov/solar/pubs/tmy2/stations.html

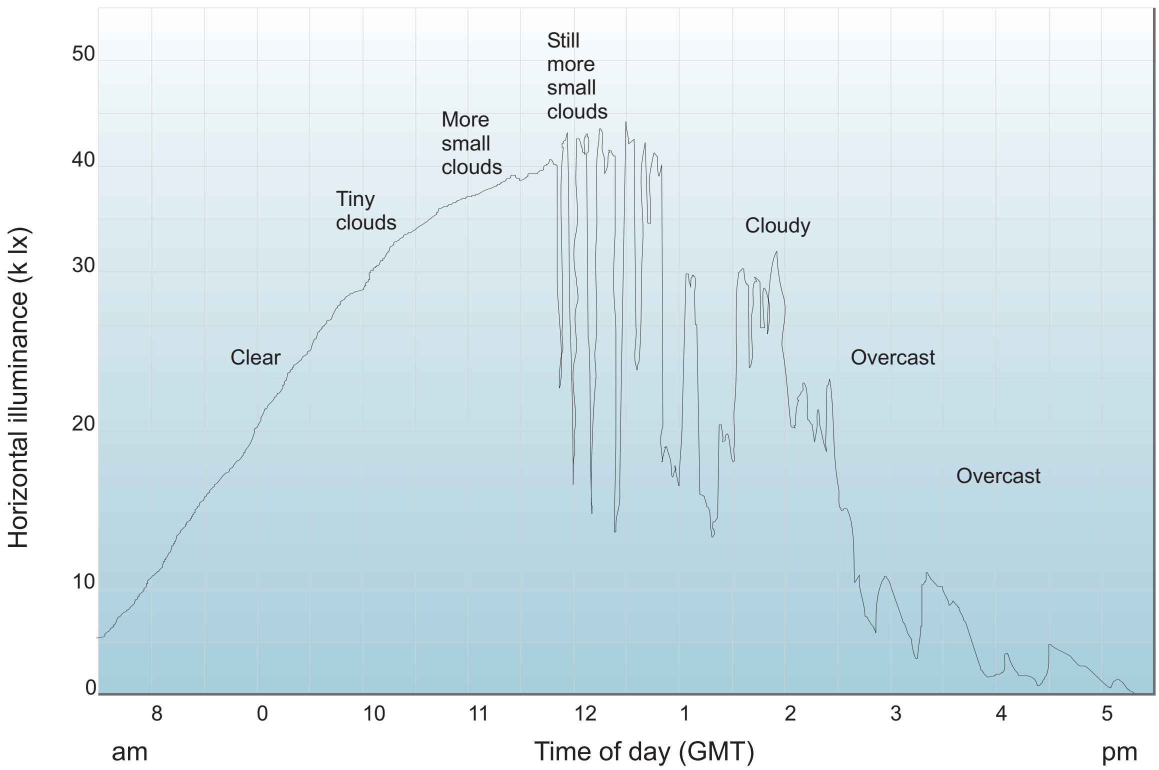


Figure 6-9 – Example of Daylight Variability

An overcast day will have much more stable illumination conditions than a partly cloudy day, but can still vary considerably with the density of the clouds. An overcast sky involves many interreflections of the sun's light, and on such a day the sky tends to be brightest directly overhead (the zenith), somewhat independent of the sun's position. In order to deal with the complexity of overcast conditions, the CIE created a standard mathematical description of the illuminance patterns across the sky dome of an standardized overcast sky, commonly called the "CIE overcast sky." It is used in many standardized daylight calculations and computer programs, but is considered most representative of overcast conditions in England and Northern Europe, where it was developed. It may not be typical, for example, of high haze conditions in U.S. deserts, or marine conditions along the U.S. coast.

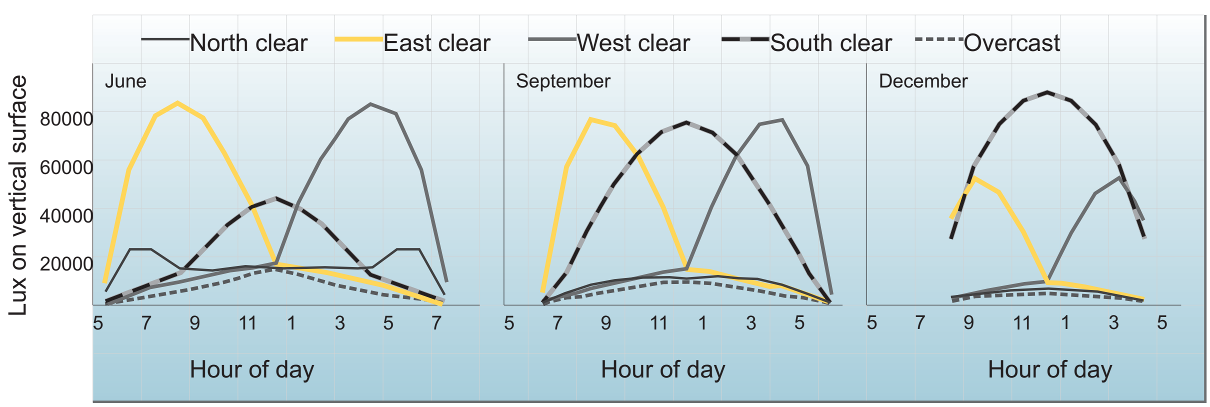


Figure 6-10 – Daylight Illumination on Vertical Surfaces by Orientation, San Francisco

Figure 6-10 illustrates the range of illumination levels by orientation, time of day, and time of year on a *vertical* surface. These values are for illumination on the *exterior* of the vertical surface, before it has been filtered by the glazing material. This clearly shows the difference in intensity between sunlight and daylight. When an orientation is facing overcast skies, or blue skies without the sun in direct view, illumination levels typically range from 5,000 to 15,000 lux (roughly 500 to 1,500 footcandles). Illumination levels dramatically increase on a clear day when the sun is in view, up to maximums of 50,000 to 90,000 lux (roughly 5,000 to 9,000 footcandles) when the sun moves directly opposite to the orientation.

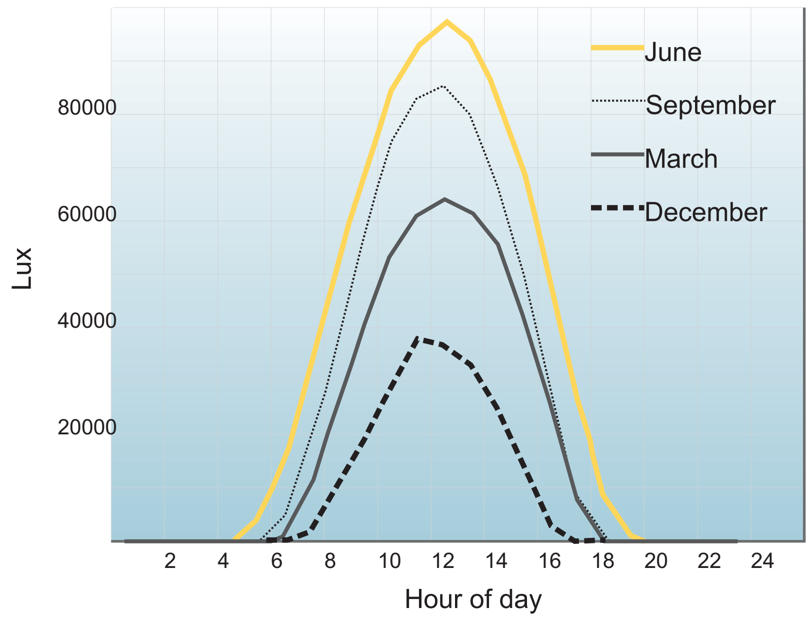


Figure 6-11 –Daylight Illumination on Horizontal Surface, San Francisco

Figure 6-11 illustrates the average hourly daylight illumination available on the exterior of a *horizontal* surface. This graph does not distinguish between clear and overcast conditions. Instead, the natural variation of weather conditions is averaged for each month. This graph shows that peak illumination in the summer, when the sun is highest, is about two and a half times greater than in the winter, when the sun is lowest in the sky. This graph also illustrates that the pattern of illumination on a horizontal surface tends to be very symmetrical around noon, similar to the pattern for a south orientation shown above.

The variability of daylight is one of its greatest assets—and challenges. Lighting designers and electrical engineers have typically been trained to analyze the relatively static lighting conditions created by electric light sources. To accommodate daylight into this static analysis, daylight conditions are often analyzed for only a few points in time, for example full direct sun and "CIE sky" overcast conditions. While this static approach may help establish the extremes, it does not help the lighting designer understand how the space responds to daylight as it changes throughout the day, and throughout the year, as sun position and cloudiness conditions change. This static approach may also not lead to appropriate decisions about the most energy efficient daylight design choices.

6.3.2 The Efficacy of Daylight

In addition to illumination, the sun also provides considerable radiation outside of the visible light range. The ratio of visible radiation to total radiation is a measure of the efficacy of sunlight or daylight. This can be expressed as a lumen per watts ratio, similar to the efficacy of electric light sources. However, rather than expressing the ratio of light output to power input, as with electric sources, the lumens per watts ratio for daylight expresses the amount of light available relative to its heat content.

The efficacy of daylight is highly variable as a function of solar position, atmospheric conditions, and cloud cover. It is important to note that sunlight has much more heat content per lumen than daylight from the sky or clouds. Once sunlight or daylight is filtered through a glazing material, this ratio also changes considerably, and depends upon the solar optical properties of the glazing material. High performance glazing materials can dramatically increase the ratio of light to heat content of daylight. More information about the effects of glazing materials on daylight is discussed in section 7.4.2.

Raw sunlight is as efficacious as the most efficient of our current electric sources, at 90 to 110 lumens per watt (lm/W). Once it is filtered through high performance glass, its efficacy can increase to 225 lm/W. Diffuse daylight is even more efficacious than sunlight, at 105 to 140 lm/W. High performance glass can increase the efficacy of daylight up to 290 lm/W, far surpassing any current electric source.

However, since the heat content and the intensity of daylight vary continuously throughout the year, it is not possible to assess the efficiency of a daylight system at one point in time. Rather, the efficiency of a daylight system should be assessed under all typical climate conditions over the course of a full year. Its efficiency will be a function of the sum of the hour-by-hour usefulness of the light contributed as it varies throughout the year, its impacts on the heating and cooling requirements of the building, and energy saved by turning off the electric lights when sufficient daylight is present.

Thus, in order to optimize the efficiency of a daylight system a designer needs to consider not just illumination conditions, but also whole building energy impacts, over the course of a whole year. This is a new challenge for lighting designers, but one which will be increasingly assisted by ever more sophisticated computer analysis tools.

Table 6-1 describes the range of performance characteristics of daylight as a light source.

Table 6-1 – Overall Performance Characteristics of Daylight as a Light Source

	Point of Reference	***Value***
Illuminance	Sunlight	2,000 – 10,000 fc (20,000–100,000 lux)
	Overcast and blue sky	500 – 2,000 fc (5000–20,000 lux)
Luminance	Overcast sky at horizon	6 x 10^5 cd /ft² (6 x 10^6 cd/m²)
	Overcast sky overhead	1.6 x 10^8 cd /ft² (1.6 x 10^9 cd/m^2)
Efficacy	Sunlight, outside of glazing	80–110 lm/W
	Overcast or clear sky, outside of glazing	105–140 lm/W
	Sunlight, inside of glazing	75–225 lm/W
	Overcast or clear sky, inside of glazing	100–290 lm/W

6.3.3 Chromaticity and Color Rendering

The variability of daylight extends to its color characteristics. The sun outside of the earth's atmosphere has a chromaticity of 5800–6000K. Clouds, dust, scattering and weather phenomena constantly modify the spectrum so that the chromaticity can routinely vary from a visually warm 1800K for sunlight at sunrise, to a cool 10,000K for a clear blue sky. See Figure 6-5 and Figure 6-6. The CIE Color Rendering Index uses daylight as a reference source and so, by definition, unfiltered daylight is always rated at 100 (R_a = 100).

6.3.4 Spectral Characteristics

The spectral distribution of sunlight is shown in Figure 6-12. One curve indicates the distribution from the sun outside of earth's atmosphere. The other curve, somewhat attenuated by the filtering effects of the atmosphere, shows the effects of absorption by water and atmospheric gases. Some molecules, such as water, have sharp absorption bands at certain wavelengths; these are illustrated as well. The visible portion of the spectrum extends from about 0.36 micron (360 nanometers) to about 0.8 micron (800 nanometers). Only about 40% of the total power of the sun at the earth's surface is visible light.

The sun's output drops substantially in the shorter wavelengths of the ultraviolet. Sunshine and daylight are rich in UV-A (315–400 nanometers), the so-called "black light" region, but there is relatively little UV-B (280–315 nanometers). This is the "actinic" or biologically active erythemel region that causes sunburn and tanning. The shorter (and dangerous) UV-C wavelengths (100–280 nanometers) are filtered out by the earth's ozone layer high in the atmosphere. (Biological effects of UV exposure are discussed in section 2.2.7.)

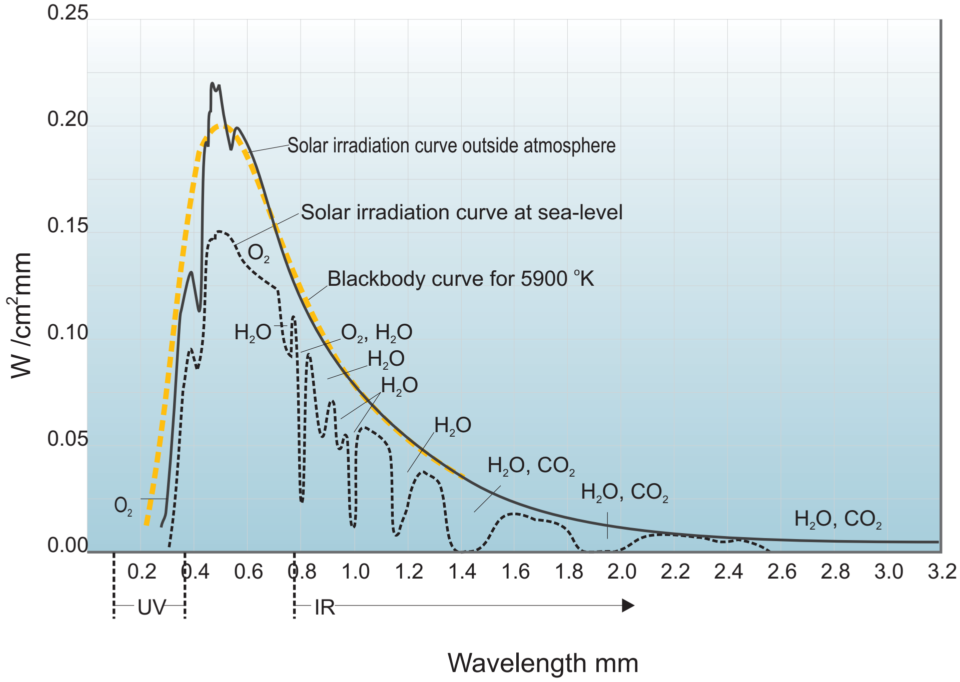


Figure 6-12 – Spectral Distribution of Sunlight

The spectral distribution of the visible sunlight that reaches the earth's surface is shown as the black dashed curve in the region between (roughly) 0.4 and 0.8 microns on this graph. Note that the curve is continuous—no major gaps—in that region and peaks at somewhat above 0.5 microns, the yellow-green portion of the visible spectrum.

Once sunlight is transformed into daylight after it reflects off molecules and particles in the atmosphere, its spectral content shifts dramatically, as some wavelengths are absorbed or reflected more than others. Figure 6-12 shows the spectral distribution of daylight under two very different sky conditions, the "cool sky" source of a clear blue sky, and the "warm sky" source with clouds reflecting low angle sunlight.

The spectral characteristics of daylight and sunlight are also changed considerably after passing through the glazing material used for a window or skylight. Tinted glass can dramatically shift the spectral balance of the visible spectrum in daylight, changing the apparent color of the light. High performance glazing materials, with spectrally selective surfaces, are designed specifically to reflect large portions of the UV and IR ranges, while leaving the visible portion of the spectrum relatively unaffected. More information about the spectral characteristics of glazing materials is discussed in section 7.4.2.

6.4 High Performance (Tungsten-Halogen) Incandescent Lamps

Incandescent lamps, while certainly the least efficacious of the general lighting light sources, nevertheless are properly used in some types of energy-efficient lighting applications. An incandescent lamp is typically the best choice when a high degree of optical control is involved (such as for accent or display lighting) or when frequent starts, flashing or other short-duty cycle operation is required that would substantially shorten the life of discharge lamps.

If incandescent lamps are indeed the best choice, then the most efficient high-performance lamps should be utilized. These now include:

- Tungsten-halogen lamps, including halogen infrared types. The latter are the most efficacious incandescent lamps.
- Capsule lamps (tungsten-halogen technology, but low-voltage, low-wattage designs).
- Enclosed projector or PAR (parabolic aluminized reflector) and reflector lamps made up of tungsten-halogen filament tubes or lamps inside of reflector optics. Included in this category are the advanced halogen infrared PAR and MR lamps. These products are sometimes called "lamps within lamps."

These three types of high performance, tungsten-halogen lamps are discussed below.

6.4.1 Technology Description

The Halogen Cycle

Tungsten-halogen lamps are compact incandescent light sources designed to operate with high-pressure halogen gas surrounding the filament and with higher filament and bulb wall temperatures than standard incandescent lamps. The higher filament temperature increases lamp efficacy and generates a "whiter" light, while the halogen gas—usually iodine or bromine—both suppresses the tungsten filament evaporation and, by a chemical regeneration process known as the "halogen cycle," redeposits evaporated tungsten on the hot surface of the filament. As a result, lamp lumen depreciation due to bulb wall darkening is practically nonexistent, and the tungsten filament also has a longer service life. Depreciation does occur due to filament degradation, but it is significantly lower than in other incandescent lamps.

Figure 6-13 – Linear Double-Ended Tungsten-Halogen Lamps

The halogen regenerative process requires that relatively high temperatures be maintained on the surface of the filament enclosure (approximately 500ºF); therefore high heat-resistant quartz glass is generally used. However, heat-resistant borosilicate glass is also now used for some low-wattage tungsten-halogen lamps.

6.4.2 Capsule Lamps

The simplest and smallest form of a general lighting tungsten-halogen lamp is a quartz or glass capsule or "bud" holding just the filament and enough space to surround the filament with gas (see Figure 6-14). The bases of capsule lamps are typically wires or pins. Capsule lamps are the most efficacious way to generate a few lumens of well-controlled or directional light since they are made in wattages down to 5 watts (60 lumens) and designed to operate at 12 volts for 2000 hours. Efficacies range from 12–19 lm/W.

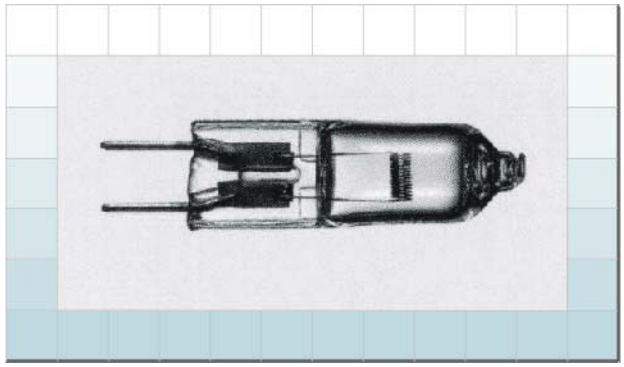


Figure 6-14 – Halogen Capsule Lamp

About Lamp Glass

There are numerous types and compositions of glass used in lamp making, but three major types predominate. The most common is "soft" or soda-lime glass. It is easily melted and blown by high-speed machines into the familiar A-line, decorative and reflector shapes. Heat-resistant, "hard" or borosilicate glass is used for weatherproof PAR or "sealed-beam" lamps. Such lamps are also called "pressed-glass reflector lamps" to indicate the process involved in their manufacture. Tungsten-halogen lamps require materials that can withstand temperatures of 3500ºC and higher within millimeters of the bulb wall, chemical attack, and pressures above 1 atmosphere. Fused silica or quartz, sometimes manufactured with additives such as alumina, is one of the few materials able to handle such rugged conditions while efficiently transmitting light

6.4.3 Lamps within Lamps

Mounting the capsule or filament tube inside of an outer envelope or reflector results in a lamp-within-lamp design. Examples are halogen PAR lamps, MR lamps (described in section 6.4.4), and halogen A-line lamps (A-shaped bulbs with a halogen filament tube inside). MR lamps have become widely used because of the size, lighting control and efficiency of the 12-volt MR-16 (2-in. diameter reflector) package.

Certain halogen A-line lamps are designed to replace 60- through 100-watt 120-volt general service lamps, but are rated for 50 through 90 watts. The life of the halogen products, however, is 2000–3500 hours rather than the 850–1000 hours typical of general service lamps.

6.4.4 MR Lamps

Characterized by a multireflector surface with faceted or segmented elements, MR lamps are available in several wattages and beam spreads for a variety of accent lighting applications. The reflector is designed to pass infrared energy out the back of the lamp, making the design essentially a "cool beam" lamp (heat in the beam is reduced by more than 60% compared to lamps with aluminized reflectors). The demand for ever-smaller lamps, however, has led to the design of an MR11 and, more recently, an MR-8 (1-in. diameter reflector). Optical performance is compromised in the smaller lamps since the ratio of filament size to reflector size determines the size, appearance and efficiency of the beam.

Another development is the recent listing of 24-volt MR-16 lamps. This permits more lamps to be connected to a single circuit or length of lighting track, but maximum candlepower and beam-spread ratings are negatively affected. Evaluating the energy efficiency of such systems is therefore more complex. But the best choice remains the system that uses the fewest overall watts to get the desired result. The analysis should consider circuit watts, not just lamp watts, so that power losses in step-down transformers are included.

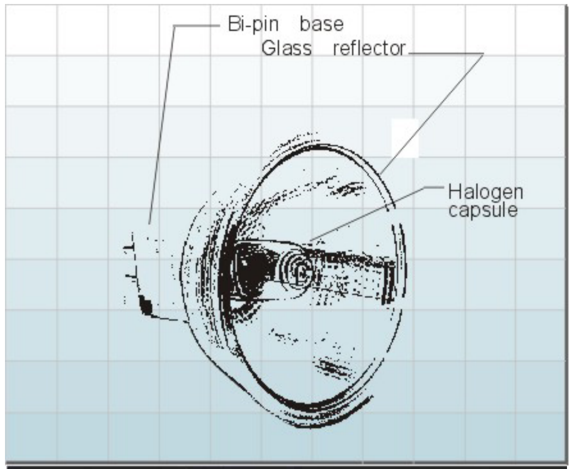


Figure 6-15 – MR-16 and MR-8 Lamp Examples
MR-8 illustration courtesy EYE Lighting.

The MR-16 lamp is made in beam spreads ranging from 7–55 degrees and in power ratings that include 20-, 35-, 37-, 42-, 50-, 65- and 75-watt lamps. Additional features include cover glass designs and "UV block" additives to the capsule glass that filter the normal UV output of the lamp down to insignificant levels.

Underwriters Laboratories (UL) listing requires that tungsten-halogen luminaires have a protective cover glass over MR lamps; however, some lamps with a built-in cover glass may be suitable for open-luminaire applications. The lamp and luminaire manufacturers should be consulted to determine which lamps may be used. (Chapter 7 discusses luminaires in detail.)

Here are some additional MR lamp considerations:

- Lamps with aluminum reflector coatings eliminate glow from the back of the MR lamp, but eliminate the "cool beam" feature as well.
- Lamps with improved dichroic coatings also reduce glow from the back of the lamp as well as providing constant color output over lamp life, longer lamp life and improved lumen maintenance.
- Lamps with color dichroic coatings (red, yellow, green and blue) are available for special lighting effects.

6.4.5 Infrared Reflecting (IR) Film Lamps

Up to 90% of the energy emitted by incandescent lamps, including tungsten-halogen types, is invisible infrared (heat). But some of this infrared energy can now be captured and reused to make the lamp more efficient. This is a key technology development, and such lamps should be evaluated for any energy-efficient application where incandescent lamps are used, particularly as new IR designs reach the market.

The basis of the technology is a multilayer dichroic coating applied to the tungsten-halogen filament tube or capsule. This transparent metallic coating is similar to the reflective surface applied to windows for “low-e” glass, with the coating "tuned" to selectively reflect infrared (IR) wavelengths back onto the lamp filament while allowing visible light to pass through and out of the lamp. The reflected infrared energy helps to heat the filament so less power is needed to keep the filament at the proper temperature. Compared to conventional tungsten-halogen designs, lamp efficacy increases are from 40–60% to the range of 28–35 lm/W (filament tube only).

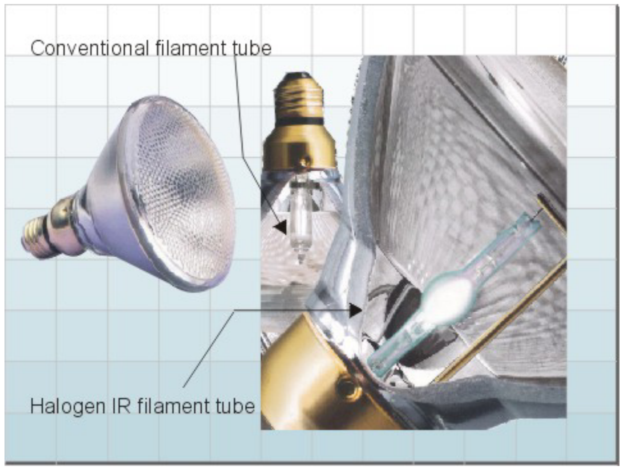


Figure 6-16 – Halogen PAR Lamp, Conventional and IR Filament Tubes
Photos courtesy GE Lighting.

IR lamps provide all of the benefits of standard tungsten-halogen lamps, including high lumen maintenance, longer life, high quality white light and easy dimmability. They are currently offered in four configurations: single-ended T-4 lamps; double-ended linear, higher-wattage T-3 lamps; PAR; and MR-16 lamps. Table 6-2 shows performance characteristics of halogen IR PAR and MR lamps.

Table 6-2 – Performance Characteristics of Halogen IR PAR and MR Lamps

Lamp	Watts	Lumens	Rated Life (Hours)	Beam Spread (Degrees)	CBCP[a] (Candelas)	Efficacy (lm/W)
PAR-30 (120 volt)	50	770	3000	9	13000	15.4
	50	770	3000	25	2700	
	50	770	3000	35	1500	
PAR-38 (120 volt)	45	600	6000	12	4000	13.3
	45	600	6000	45	1100	
	50	850	3000	10	14000	17.0
	50	850	3000	25	3000	
	55	780	6000	12	9000	14.2
	55	780	6000	40	2000	
	60	1110	3000	10	20000	18.5
	60	1110	3000	12	12000	
	60	1110	3000	25	5100	
	60	1110	3000	30	3600	
	60	1110	3000	40	2000	
	80	1500	3000	10	25000	18.7
	80	1500	3000	12	19000	
	80	1500	3000	25	5500	
	90	1470	6000	12	12000	16.3
	90	1470	6000	40	2800	
	100	2070	3000	10	29000	20.7
	100	2070	3000	25	6300	
	100	2070	3000	40	3400	
MR-16[b] (12 volt)	37	-	4000	10	11500	-
	37	-	4000	25	3500	-
	37	-	4000	40	2050	-
	50	-	4000	10	15000	-
	50	-	4000	25	5100	-
	50	-	4000	40	2500	-

[a]Center Beam Candlepower

[b]37- and 50-watt IR MR lamps are designed to replace 50-watt and 65–73-watt conventional MR lamps respectively.

It is technically feasible to incorporate IR technology into household "A-line" lamps; indeed that has been done on an experimental basis. However the lamp's cost is beyond the energy savings payback at some residential energy rates and, so far, has been judged too expensive for the consumer market by the manufacturers.

6.4.6 Halogen Lamps—Unique Life and Failure Characteristics

Lamp life ratings for tungsten-halogen lamps are generally 2000 hours or more, with some PAR and MR lamps now rated as high as 6000 hours. As a tungsten-halogen lamp burns, the gases involved in the halogen cycle capture evaporated tungsten and redeposit it onto the filament. Unfortunately, there's no mechanism for returning the tungsten to the original location, so the filament eventually becomes brittle and thin. Hot spots develop and finally the filament disintegrates, often just as it is heating up rapidly during turn-on or when the lamp is subjected to physical shock or vibration. The lamp seals (the region where the electrical leads enter the filament tube) are critical parts of the lamp. Some lamp failures are due to excessive seal temperatures or damaged seals that cause cracks in the glass or quartz filament tubes, allowing air to oxidize the filament.

Some 120-volt tungsten-halogen lamps are prone to "hot shock" failures—a condition where the coils of the filament are shorted out by physical shock while the filament is operating. Use caution so as not to jar energized lamps during installation and aiming. Low-voltage halogen lamps (those rated for 6, 12 or 24 volts) and particularly high-wattage, low-voltage lamps are relatively shock resistant and are the preferred choice where there's the continuing likelihood of significant shock or vibration.

The life of any incandescent lamp is strongly dependent on the applied socket voltage. A lamp rated for 120 volts will lose 20% of its rated life when operated, on average, at only 2% (or 2.4 volts) over its rating. Operating an incandescent lamp at reduced voltage will increase lamp life, but the light output decreases faster than the power use.

6.4.7 Dimming Halogen Lamps

Tungsten-halogen lamps, like other incandescent lamps, can be easily dimmed over their full range of output with voltage control or phase control (electronic) dimmers. Dimming reduces the temperature of the filament, which rapidly reduces lamp efficacy, so dimming tungsten-halogen lamps should be done only for architectural and aesthetic reasons, not as an energy-saving strategy. For example, dimming a lamp to half light output only drops the power to the lamp by about 25%. For more about dimming, refer to chapter 8.

Tungsten-halogen lamps can be dimmed with conventional incandescent dimmers, generally without any special considerations. However, each lamp type will have some output level below which the filament tube temperature will be too low for the halogen cycle to operate. Theoretically, this could cause the filament tube to darken, the light output to drop and, in extreme cases, the lamp to fail. But since in the dimmed mode the filament temperature is also low so that only minimal amounts of tungsten are evaporating, lamps typically perform well when dimmed. If any filament tube darkening is noticed, operating the lamp at full power for a few seconds will "clean up" the lamp.

Low-voltage lamps such as the MR types that operate on 12 or 24 volts through a transformer or electric step-down device can be dimmed, but a special dimmer designed for use with the step-down device is required.

6.4.8 Application Guidelines

Performance Characteristics

The following performance characteristics are suggested to fully specify a halogen lamp for a lighting application:

- Initial lumens
- Rated watts
- Rated life
- Maintained lumens or lumen maintenance. This characteristic is often expressed as a graph or lumen maintenance curve, but may also be given as "mean" lumens over lamp life or LLD (lamp lumen depreciation), which is defined as the light output of the lamp at 70% of rated life. For more about lumen maintenance, see section 6.2.3.
- Rated voltage. This is a critical value for incandescent lamps since even a 2% change in applied voltage will change light output by 6% and life by 20%.

- Color (chromaticity and color rendering index [CRI]). The CRI of any unfiltered halogen lamp is 99–100. Chromaticity may be given either in "x-y," CCT or color temperature. Refer to section 6.2.4 for more about color appearance.
- Lamp description and manufacturer's lamp code
- For certain light sources, especially reflector lamps, more detailed performance information may be required, including:
- Intensity data—Center beam candlepower and beam spread or candlepower distribution data (reflector lamps). These data may be shown in graph form as a "candlepower distribution curve."
- Spectral distribution data (including UV output)
- Bulb type
- Base type
- Filament construction
- Dimensional data
- Light center length. This dimension is the distance between the end of the lamp base and the center of the light-emitting region. It is typically used for reflector or refractor design.
- Burning position requirements

High-performance Incandescent Lamp Nomenclature

Although there is little standardization among manufacturers where specifications for their high performance incandescent products are involved, they have generally maintained the traditional practice of starting their incandescent lamp ordering codes with the lamp wattage.

Single-envelope tungsten-halogen lamps with quartz envelopes usually have a "Q" in the ordering code. Some lamps may also be listed with a three-letter ANSI designation, a carryover from the time when most tungsten-halogen lamps were used for stage/studio applications.

But the descriptions "tungsten-halogen," "halogen," and "quartz" don't necessarily refer to the same product, and therefore they shouldn't be used interchangeably. Many of the tungsten-halogen capsule lamps don't use quartz because that makes the lamp more expensive. Although most quartz lamps are tungsten-halogen lamps, not all tungsten-halogen lamps are quartz lamps.

Specifying Beam Characteristics

Halogen reflector, PAR and MR lamps are available in a bewildering variety of beam spreads. The specifier must be exacting in his or her selection as there is a distinct possibility of different beam spreads from different manufacturers even though ordering codes appear the same. Be cautious when selecting between a generic specification and a proprietary specification; a visual examination of the patterns generated by the lamp may be required in critical situations. Figure 6-17 provides examples of reflector lamp beam characteristics.

Rapid development and market-driven lamp product introductions have resulted in some needed changes in the nomenclature used for reflector lamps. Instead of the traditional "FL" and "NSP" to indicate "flood" or "narrow spot" distributions, for example, reflector lamp beam spreads are now being indicated in degrees or with a combination of the old and new designations, such as "SP10" to indicate a lamp with a spot distribution of 10 degrees.

In general, a manufacturer's lamp designation would be expressed as: (Quartz)/Wattage/Bulb shape/(Manufacturer's feature designation)/Beam spread. For example, a 90-watt halogen capsule PAR-38 narrow spot lamp with a 10 degree beam would be: 90PAR/H/SP10°. Another manufacturer might designate a similar—although not exactly the same—product as: 90PAR/CAP/NSP. To give another example, a 50-watt MR-16 lamp with a narrow flood (25 degree) beam spread (EXZ) would be designated as 50MR16N/NFL25 or perhaps 50MR16-EXZ.

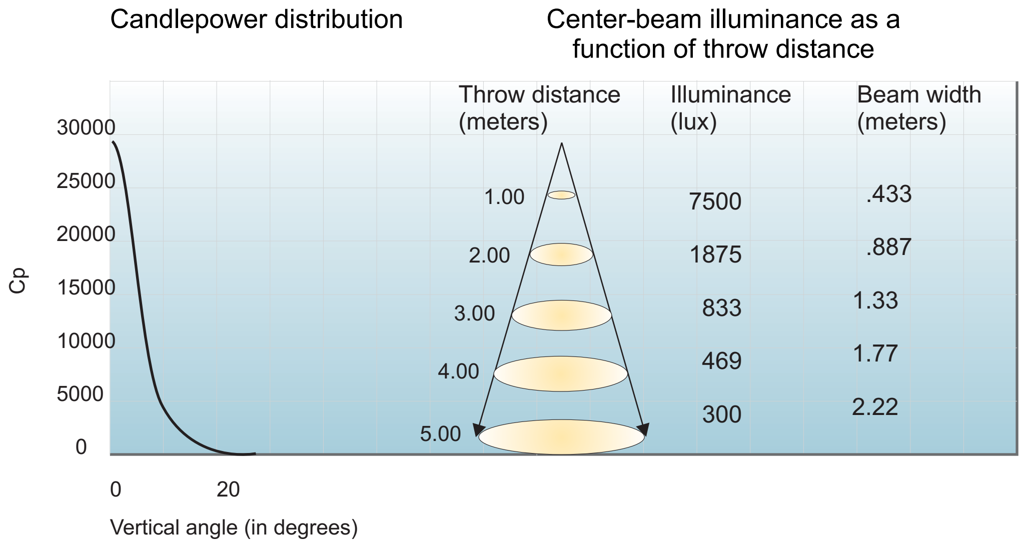


Figure 6-17 – Example of Reflector Lamp Beam Characteristics
This figure shows candlepower (CP) vs. angular distance from the center of the lamp beam and center-beam illuminance as a function of throw distance.

6.5 Fluorescent Lamps

Fluorescent lamps emerged from the lamp laboratories as commercial products in 1937–38 and began to be used in quantity after World War II. By the 1950s, incandescent lamps were no longer the norm for new general lighting systems in commercial and industrial applications and by the 1960s more than two-thirds of the light (lumen-hours) generated in commercial and industrial facilities in the United States was being produced by fluorescent sources. The lighting industry later referred to this period as the "age of abundance"—a time when the cost of light (expressed as $/million lumen-hours) fell and illumination levels increased. A lumen of light could be generated from fluorescent lamps at roughly 25% of the cost of a lumen from incandescent lamps. In addition, lighting system maintenance costs dropped as fluorescent ballast reliability improved and the rated life of fluorescent lamps, originally only 1000 hours, increased to 10,000 and then to today's 20,000 hours and higher.

More recently, as the cost of electric energy has increased, the cost of fluorescent lumens has remained steady or has even dropped in real terms due to increases in lamp/ballast system efficacy.

6.5.1 Technology Description

Fluorescent Technology Drivers

Fluorescent systems are the focus of some of the best technology in the lighting industry because of their widespread use and the highly competitive nature of the business. The major technologies driving new higher efficiency fluorescent systems are:

- *High-frequency electronic ballasts.* Operating fluorescent lamps at high frequencies (above 10 kHz) reduces cathode losses for a lamp efficacy gain of about 10% compared to 60 Hz operation.
- *Smaller-diameter lamps.* Efficacy gains occurred when lamp diameters were reduced from T-12 (1.5 in.) to T-8 (1 in.); but similar gains for the next step to T-5 (0.625 in.) lamps, if realized, will be due to both lamp and optical efficiency increases.

- *Improved phosphors.* "Three-peak" or "rare-earth" (RE) phosphors with improved color rendering properties and a broader selection of chromaticity have now become the industry standard, replacing the older halophosphate phosphors that characterized the widely used, but now obsolescent "cool white" and "warm white" lamps. Rare-earth phosphors maintain their efficiency over time better than the halophosphors and so provide more than a 4% lamp efficacy improvement by themselves.
- *Low-mercury lamps*. Mercury cannot, at this point, be eliminated from fluorescent lamps because there is no practical alternative way of generating the short-wavelength UV needed to excite lamp phosphors. The amount of mercury in fluorescent lamps can be reduced, however. Using the F40T12 lamp as the measure, the mercury needed to power the lamp has dropped from about 50 mg/lamp (industry average) to less than 10 mg/lamp without significantly affecting rated performance. This assists lamp manufacturers to design lamps that pass the Federal EPA Toxicity Characteristic Leaching Procedure or TCLP test. Fluorescent lamps that pass the test are not considered hazardous waste and therefore do not require special disposal procedures except in several states that have more stringent regulations than federal law. For more about mercury in lamps, see section 3.2.
- *Internal lamp coatings*. These made possible low-mercury fluorescent lamps and lamps with improved lumen maintenance since the migration of mercury into the phosphor and glass is minimized. The lumen maintenance of high-volume linear fluorescent lamps with RE phosphors is now at 95% (mean lumen rating). See Table 6-3.
- *Advanced ballast circuitry.* Electronic circuitry now being incorporated into high-frequency ballasts carefully starts fluorescent lamps and then provides the proper "diet" of controlled crest factor current and voltage to the lamp, sensing what to do as the lamp characteristics change over life. The benefits are longer lamp life due to minimal cathode sputtering and less depreciation of lamp output.
- *Amalgam lamps*. The ambient temperature range over which fluorescent lamps operate at maximum output and efficacy is broadened by the use of mercury amalgams inside the lamp to control mercury vapor pressure. Now commonly found in compact fluorescent lamps (CFLs), amalgams make possible smaller luminaires and more compact, but optically efficient, lamps.
- *Electrodeless fluorescent lamps*. In discharge lamps, cathodes cause starting, life, lumen maintenance and manufacturing problems. Eliminating the cathodes adds system complexity, but promises significantly longer lamp life, less lamp depreciation and efficacies comparable to conventional systems.

Fluorescent Lamp Life

The lamp cathodes are usually the main life determinant. Cathodes are designed as coils of tungsten wire at the ends of the lamp and are coated with an "emission mix"—a chemical compound that emits electrons when heated. The emission mix sputters off during starting and burns off slowly during normal lamp operation. When the emission mix is gone from one of the cathodes, the lamp becomes unstable or will not start. Lamp failure may also be due to mercury "starvation" since as the lamp burns normally, mercury slowly migrates into the phosphor and the lamp's cathodes, leaving less to sustain the arc.

Since fluorescent lamp life is dependent upon sufficient mercury remaining in the lamp until normal cathode failure, the challenge for lamp manufacturers is to reduce mercury while maintaining rated lamp life. Current published lamp ratings suggest that manufacturers are confident that they have. If there are questions from a specification or user standpoint, however, the solution is to request a lamp performance warranty from the manufacturer spelling out the life ratings in detail and the remedy in case of short lamp life.

Dimming Fluorescent Lamps

Fluorescent lamps cannot be properly dimmed with the same simple wallbox devices typically used for dimming incandescent lamps; instead, a special control and dimming ballast must be used. There is an exception to this general rule: Some types of screw-in compact fluorescent lamp with integral ballast can indeed be dimmed by such simple controls. As an advanced lighting guideline, however, where the emphasis is on permanent energy-saving systems, dedicated fluorescent dimming equipment is recommended.

Should Fluorescent Lamps Be "Seasoned" Before Dimming?

Should fluorescent lamps be "seasoned" or burned at full power for a period of time before dimming them? Recommendations from lamp and dimming control manufacturers may differ. At the heart of the question is two issues: (1) observations that fluorescent lamps change significantly in output during the first few hours of operation; and (2) the longstanding industry practice of testing and rating fluorescent lamps only after the first 100 hours of burning.

New fluorescent lamps go through a stabilization process as phosphor particles and impurities settle out of the arc path, the cathodes burn off excess material, and mercury distributes itself according to the lamp's temperature profile. Therefore, dimming the lamp when new may result in flickering and lamp striations (instability) at low dimmer settings and may slow the stabilization process, according to lamp manufacturers. One control manufacturer also reports short lamp life if compact fluorescent lamps are not seasoned.

There are some unpublished data indicating that briefly seasoning lamps (10 hours or so) in multiple lamp systems—especially where lamps of different lengths and types are used—improves low-end dimming and lamp "tracking." This somewhat nebulous term relates to the quality of the dimming process involving lamp brightness and "smoothness" as the lamps are dimmed.

Conclusion: Burning new fluorescent lamps—especially compact fluorescent lamps—at full power for 10 to 24 hours before dimming will speed the seasoning process and minimize problems related to lamp life and dimming quality. NEMA has been asked to develop a consensus recommendation on the issue. That is expected during 2001.

For full-range dimming without a reduction in lamp life, fluorescent lamps require that the lamp cathode and starting voltages be maintained as lamp power is reduced. This is most easily done with rapid-start circuits; thus rapid-start lamps are the only types suitable for dimming applications. The power required to keep the cathodes properly heated over the full dimming range means that fluorescent dimming systems are less efficient when operating lamps at dimmed levels; however, as indicated in Figure 6-18, lamp efficacy remains relatively high until lamp light output drops below 40%. Note particularly the differences in lamp efficacy between fluorescent and incandescent lamps when they are dimmed.

While any rapid-start fluorescent lamp can be dimmed, the practicalities of the marketplace have limited the availability of dimming ballasts and controls to the most widely used types of linear and compact fluorescent lamps.

For more information on dimming ballasts, see section 6.5.3 and chapter 8.

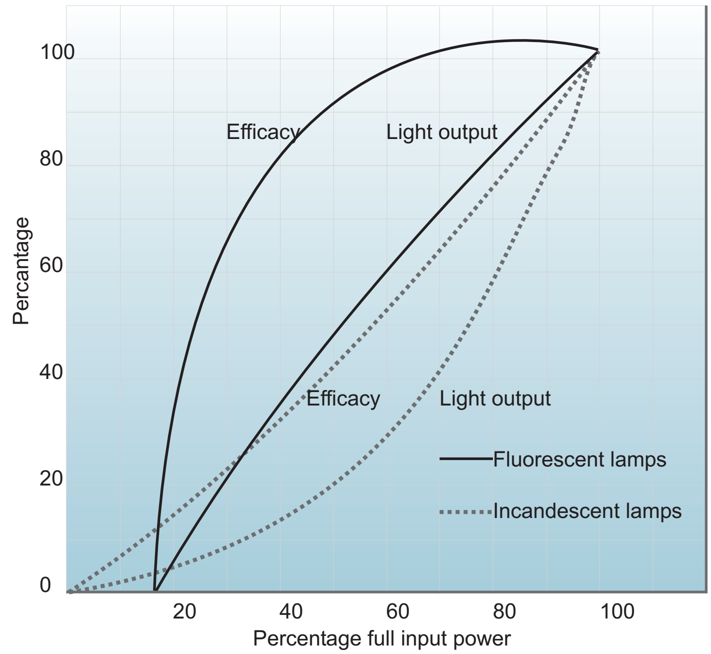


Figure 6-18 – Lamp Output & Efficacy vs. Power, Fluorescent and Incandescent Dimming
Source: Coaton and Marsden 1997.

6.5.2 Linear Fluorescent Lamps

Linear fluorescent lamps are the bellwether lamps for commercial and industrial lighting because of the large quantities in service. Performance enhancements tend to be implemented in these lamps first This category includes 2-, 3-, 4- and 5-ft rapid start lamps, 6-ft and 8-ft "slimline" lamps, 8-ft high output or "HO" 800 mA rapid start lamps, and 4-ft lamps bent into "U-tube" configurations and designed for 2-ft modules.

T-12, T-8 and T-5 linear fluorescent lamp technologies are briefly described below; their performance is compared in Table 6-3.

T-12 Lamps

Until fairly recently, the F40 or F40T12/RS has been the most popular linear fluorescent lamp in North America, constituting more than 50% of the total population of fluorescent lamps sold. Energy legislation and the development of lower wattage alternatives shifted the use of 4-ft lamps toward the reduced wattage version, the F34T12/RS. Now, however, the T-12 lamp is headed toward obsolescence as more efficient alternatives—mainly T-8 designs—are utilized.

T-8 Lamps

Efficient T-8 lamp technology depended on the development of phosphors that could withstand high bulb wall power loading without rapid depreciation compared to T-12 designs. That hurdle was overcome with the development of rare-earth (RE) phosphors in the 1970s and their incorporation into both linear and compact fluorescent lamps during the 1980s. Higher efficacy and smaller size, which equaled less volume for shipping and storing lamps, as well as smaller luminaires, appealed to the marketplace. Now the T-8 is becoming predominant, with the F32 (32 watt), 4-ft T-8 being the preferred choice. Some of the impetus for change was and remains due to the ease with which T-12 systems can be retrofitted to T-8 lamps. The main driver, however, is economic, with the promotional efforts of utilities and energy agencies and energy-based rebate programs that "jump-started" T-8 demand.

T-5 Lamps

T-5 lamps represent the next generation of linear lamp technology, incorporating features from both T-8 linear and T-5 twin-tube lamps. They are the first linear fluorescent lamps for general lighting to be made in metric lengths in North America (except for some special T-8 and T-12 lamps made for certain applications in Canada). There are two T-5 designs: standard and high output (HO).

Table 6-3 – Performance Comparison of T-12, T-8 and T-5 Linear Fluorescent Lamps

Lamp Type[a]	Length MOL[b]	Rated Watts	Rated Lumens[c]	Mean Lumens	Rated Life[d] (Hours)	Efficacy (Lm/W) (Mean)	Avg. Lamp Luminance
F40T12	48 in. (1219.2 mm)	40	3300	2970 (0.90)	20000	74.3 (82.0)[e]	800 cd/ft² 8000 cd/m²
F32T8	48 in. (1219.2 mm)	32	2950	2800 (0.95)	24000	87.5 (96.0)[e]	1200 cd/ft² 12000 cd/m²
F28T5	45.8 in. (1163.2 mm)	28	2900	2755 (0.95)	20000	98.4	2000 cd/ft² 20000 cd/m²
F54T5/HO	45.8 in. (1163.2 mm)	54	5000	4750 (0.95)	20000	92.6	3400 cd/ft² 34000 cd/m²

[a] All lamps are manufacturers' premium-performing products, RE841 color.

[b] Nominal length. MOL = Maximum Overall Length.

[c] T-8 and T-12 lamps are rated at 60Hz and 25°C. T-5 lamps are rated at high frequency and 35°C.

[d] Rated life at 3 hours/start. T-5 lamps are rated on a high frequency, programmed-start ballast.

[e] Estimated mean efficacy at high frequency.

The data in Table 6-3 confirm that, even on high-frequency ballasts, the T-12 lamp is obsolete from a performance standpoint and should be replaced (lamp and ballast) by T-8 lamps operated on high-frequency ballasts. This is a relatively simple retrofit.

T-5 lamps are not a retrofit opportunity because of:

- their metric lengths
- lamp holder design
- little to no efficacy improvement over T-8 lamps; and
- substantially higher tube luminance, which is likely to cause glare problems in existing lighting equipment where the lamp can be viewed directly, even through a lens or diffuser.

Rather, the T-5 lamps are likely to be best used in new luminaires designed around their smaller size, unique lengths and thermal characteristics. See chapter 7 for recommended luminaires and applications. For energy comparisons of similar systems, see Table 7-4.

Fluorescent Lamp Nomenclature

Fluorescent lamp designations have become complex as lamp types have proliferated; also, lamp manufacturers tend to use their own trade names as part of the codes. In addition, the National Electrical Manufacturers Association (NEMA) codes may also be shown in catalog listings if the lamps are not unique to one manufacturer.

Descriptions of linear lamps are the most consistent and typically begin with an F followed (usually) by numbers that indicate lamp wattage or lamp length in inches. Then the lamp diameter is shown as a T (for tubular) followed by a number indicating the diameter of the tube in eighths of an inch. A T-8 lamp is therefore 8/8 or 1 inch in diameter. The rest of the code describes the color of the lamp, finish or circuit type. The code F32T8/735/RS, for example, indicates a 32-watt T-8 rapid-start lamp with a 3500K, 70–79 CRI phosphor.

Color rendering index and correlated color temperature ratings are combined into a 3-figure suffix. The first figure is the CRI band (e.g., 6=60-69, 7=70-79, 8=80-89, etc.). The last two figures indicate the color temperature (e.g., 30=3000, 65=6500, etc.).

6.5.3 Energy-efficient Fluorescent Ballasts

The lighting industry has followed two paths in recent years toward the goal of improving fluorescent lamp system efficiency. The first was a "make it better" approach that optimized existing lamp and ballast performance, with the focus on T-12 systems. That resulted in a 10–20% improvement in system efficacy.

The second approach—using solid-state electronics to provide high-frequency controlled power and optimum starting to fluorescent lamps—has successfully increased lamp/ballast system efficacy by as much as 30–40% and added the capability of additional features at low cost. These features include fluorescent lamp dimming, enhanced control capability and improved lamp life performance.

Electronic Ballasts

Electronic ballasts or, more properly, electronic high-frequency ballasts, increase lamp-ballast efficacy, leading to increased energy efficiency and lower operating costs without sacrificing light output. Electronic ballasts operate lamps using electronic switching power supply circuits. These circuits take incoming 60-Hz power (typically 120 or 277 volts) and convert it to high-frequency alternating current (AC) in the range of 20–40 kHz. Electronic ballasts are more efficient than magnetic ballasts in converting input power to the proper lamp power. Operating fluorescent lamps at higher frequencies reduces internal lamp losses resulting in an overall lamp-ballast system efficacy increase of 15–20% compared to efficient electromagnetically ballasted systems.

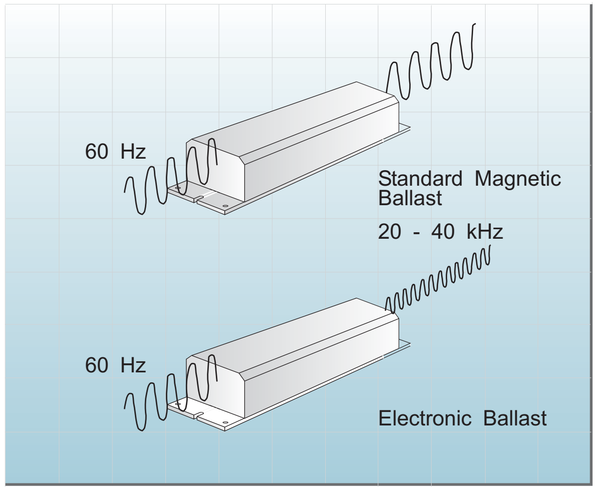


Figure 6-19 – Magnetic and Electronic Ballasts

Both traditional electromagnetic and high-frequency electronic fluorescent ballasts utilize standard 60-Hz input power. The electromagnetic ballast merely regulates the 60-Hz power and sends it to the lamp. The electronic ballast transforms the input power to a high-frequency (20–40 kHz) before sending it to the lamp. This results in lower lamp and ballast losses and a higher system efficacy—as much as 30%.

Ballast Terminology

Ballast Power Factor: The ratio of the root mean square (RMS) power (watts) to the volt-amps (VA) of the ballast. The power factor of the electrical loads, such as ballasts, on a system determine the overall power factor of the building electrical system. That measure is an indication of how efficiently electrical power is being transferred from the source to those building loads. (Note: power factor does not measure how efficiently the power is being used by the building loads). A high power factor (HPF) rating of a ballast signifies a desirable power factor equal to or greater than 0.90. A low or "normal" power factor (NPF) rating signifies a power factor less than .90—usually between .40 and .70. Electric utilities may penalize customers whose overall building load has a low power factor since this lowers the transmission efficiency of the utility's system.

Input Voltage: The design operating voltage of the ballast. In the United States, most ballasts are designed to operate at either 120 or 277 volts.

Lamp-Ballast System Efficacy: The ratio of lamp light output to ballast input watts, in units of lumens per watt.

Line Current Amps: The current drawn by the ballast when operating at rated voltage.

Lamp Current Crest Factor (LCCF): The ratio of the peak current to the root mean square (RMS) lamp current. The LCCF for lamps operated at high frequency is equal to the peak current of the modulated wave (60 Hz) divided by the RMS lamp current. High current crest factors reduce lamp life and increase lamp depreciation. Life ratings for lamps are based upon an LCCF of 1.7 or less.

Regulation (of line voltage): The ability of the system light output to adjust for input voltage variations. Generally expressed as a percentage variation in light output of a lamp for a percentage variation in input voltage.

Volt-Amps: The apparent power of a system. It is equal to RMS of voltage times RMS of current.

Electronic ballasts have a number of other advantages over magnetic ballasts:

- Multiple lamp operation. Electronic ballasts are readily available that operate from one to four lamps.

- Lamp operation may be either in series or parallel mode by choosing the appropriate ballast type. The advantage of parallel mode is that a single lamp failure will not affect the operation of the remaining lamps controlled by the same ballast. Ballast losses, however, are slightly higher with parallel mode than series mode.
- They are lighter in weight.
- They are quiet.
- Lamp flicker is eliminated.
- They are directly interchangeable with magnetic ballasts.
- Models are available to operate most full-size and compact fluorescent lamps.

Ballast Factor

A lamp/ballast system's ballast factor (BF) is the decimal fraction of the actual lumen output for a specific lamp-ballast divided by the rated lumen output measured with a reference ballast under ANSI test conditions (open air at 25°C [77°F]). Ballast factors became important when lamp/ballast combinations proliferated during the 1970s and designers found that there could be substantial light output variations from luminaires depending upon the lamp/ballast combination used.

It's important to understand that ballast factor is not a measure of energy efficiency. A ballast factor less than 1.0 means that the lamp on a particular ballast will operate at less than its rated output. The lamp also consumes proportionally less power as well, so lamp efficacy remains relatively constant. Electronic ballasts are now available with several ballast factor ratings including ballast factors over 1.0, which means that the lamp will operate at more than rated watts and light output. A choice of ballast factor allows designers to better minimize energy use by "tuning" the lighting levels in the 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 factor ballasts may be more appropriate.

A wide range of ballast choices are available to lighting practitioners, allowing them to attain their lighting objectives more efficiently. Technically possible now are electronic ballasts whose ballast factors can be set as the ballast or luminaire is installed or ballasts where the BF might be programmed and changed via a control system.

Lamp-Ballast System Efficiency

The efficiency of a fluorescent lamp ballast changes depending on the type of lamp operated. Similarly, lamp efficacy is affected by ballast technology: the same lamp will perform differently when powered by an electromagnetic (EM) ballast than it will when operated at high frequency. As a consequence, the only meaningful comparison between lamps or ballasts is the lamp-ballast system efficacy. The system efficacy can be calculated as follows:

$$\text{System efficacy (lm/W)} = \frac{\text{Rated lamp lumens}}{\text{Input power}} \times \text{Number lamps per ballast} \times \text{Ballast factor}$$

Equation 6-1

Electronic Ballast Types

Rapid-start Electronic Ballasts

As with older EM ballasts, rapid-start (RS) electronic ballasts heat lamp electrodes continually during starting and operation. But electronic RS ballasts are available for one-, two-, three- and four-lamp operation. Some ballasts can operate either T-8, T-10, or T-12 lamps. However, the ballast factor won't be the same for all lamp types, and lamp operation may not be in accordance with the lamp manufacturer's recommendations. Also, different lamp types shouldn't be mixed on the same ballast. They will operate at different power levels and therefore will appear different in brightness.

Instant-start Electronic Ballasts

Instant-start (IS) fluorescent ballast circuits apply a relatively high voltage to the lamp to quickly start the lamp and heat the lamp cathodes. There is no separate cathode-heating circuit as with RS systems. IS operation is therefore slightly more efficacious since less power is used to heat the cathode, but the lamp cathodes are subject to more wear and tear during the starting process and lamp life may be reduced. Recently, however, lamp and ballast manufacturers have jointly developed systems optimized for IS operation and may rate IS lamp life the same as RS lamp life for particular lamp/ballast combinations and for certain hours/start situations.

Occupancy sensors should not be used with instant-start lamp-ballast systems because frequent lamp starting will typically reduce lamp life. Use rapid-start systems for such applications. Better yet, use "programmed-start" rapid-start systems that minimize cathode deterioration (see Programmed-Start Ballasts below). Lamp life on such systems is typically rated the same as "continuous burning" operation. For more about occupancy sensors, see section 8.3.

Two-level Electronic Ballasts

Two-level or "step" electronic ballasts increase the flexibility of standard electronic ballasts by allowing the system light output to be switched between a low (typically 50%) and full output level. Standard switches, occupancy sensors, photocells, or other building energy management control devices may be used to switch the ballast. It's designed to be a low-cost, easy-to-install system using simply an additional input lead for the switching circuit. Refer to chapter 8 for details about control devices.

Electronic Ballasts for Partial and Full-range Dimming

State-of-the-art electronic ballasts with dimming circuitry permit the light output of the lamp to be smoothly and continuously controlled over a wide range. The highest or "architectural" grade dimming ballasts dim from approximately 100% to 1% of full light output. Less expensive dimming ballasts may offer minimum settings of only 5% to 20% of full light output and are frequently specified for use in systems where simple energy management strategies are employed, such as tuning (adjusting the level of a lighting system to match a defined illuminance pattern), daylight compensation or occupancy patterns. All fluorescent dimming ballasts operate the lamps in rapid-start mode and are equipped with circuits that maintain lamp cathode voltage as the lamp power is reduced. This not only permits dimming, but also permits operating the lamp for extended periods at any light output level without reducing lamp life.

There is no universally used standard system or dimming protocol for fluorescent dimming ballasts; rather, there are several systems in common use. From a specification and design standpoint, the ballast should be matched to the control by specifying a "system" with all components supplied by the same manufacturer or by carefully following the ballast manufacturer's specifications.

Expect to find the following systems in the marketplace:

- *0-10 Volt.* Each ballast requires four feed wires—two for power and two (low voltage) for control. This system is fairly widely used and numerous control devices—such as daylight sensors—are available for it. The controls are relatively simple and low cost, but the control wiring must be run to each ballast and so this system is typically more easily installed in new applications.
- *Two-Wire.* As the name suggests, only two wires are required between the control and the dimming ballast, so this system can often be retrofitted at low cost. It was first designed for manual control arrangements. Linking to automatic systems remains complicated because there are relatively few manufacturers and the availability of interface components is limited.

- *Three-Wire.* This system is similar to those once used with electromagnetic ballasts, so it is familiar to designers and installers and it is backward compatible with some existing systems. Each ballast requires three feed wires—two for power and one (line voltage) as the control lead.
- *Digital.* Designed in as part of the digital circuitry used in some electronic ballasts, these systems are relatively new and currently utilize four feed wires—two for power and two (low voltage) for the digital signal. The digital signal could, however, be provided via the power wiring.

Long-term, digital controls are expected to offer the most flexibility at the lowest cost since, for example, an individual ballast could be programmed with a digital address and then controlled on a ballast-by-ballast or even a lamp-by-lamp basis using computer-based control equipment. For more about controls, see chapter 8.

Programmed-start Ballasts

Starting a fluorescent lamp causes more cathode deterioration than operating that lamp over a given period of time. Typical lamp life ratings, as provided by the lamp manufacturer, are based on three hours of lamp operation per start, so significantly shorter operating periods—such as those resulting from lamps used with occupancy sensors, timers or automatic control systems—can shorten absolute lamp life, while simultaneously lengthening calendar life. Correspondingly, longer burning periods lengthen absolute lamp life. Manufacturers sometimes publish "continuous-burning" lamp life ratings, which are the maximum for a particular lamp type.

Recent research and lamp testing have indicated that a starting "scenario" or carefully controlled starting process can reduce or eliminate the usual cathode deterioration, thus lengthening lamp life to the "continuous burning" rating. Ballasts incorporating this starting scenario are called "programmed-start" or "soft-start" ballasts.

In the rapid-start version, the ballast initiates the starting process by heating the lamp cathodes while eliminating any "glow current"—the discharge or ionization of the gases surrounding the cathodes. Once the cathodes reach their proper operating temperature (usually 700ºC), the lamp arc is started as quickly as possible. Tests that cycle the lamp on and off repeatedly indicate that lamps operating on programmed-start ballasts can withstand 30,000–40,000 starts before failing, whereas lamps on standard ballasts can withstand only 18,000–20,000 starts.

End-of-life-sensing Ballasts

As fluorescent lamps reach their normal end-of-life, the cathodes deteriorate as the coating material ("emission mix") on the cathode wires is burned away. Normally, that causes the starting voltage of the lamp to increase beyond what the ballast can reliably supply and the lamp begins to flicker or simply does not start. Electronic ballasts, however, can supply significantly higher starting voltages to lamps, and the high-frequency power tends to travel on the surface of, rather than through, the conducting materials. The result is that deteriorated cathodes may operate in the instant-start mode as the lamp fails, or worse, may disintegrate and force the arc to land on a lead or support wire. If this happens, the heat of the arc begins to melt the wire or the lamp may "rectify" and draw a large current that melts the cathodes and the surrounding glass structure and blackens the plastic base and socket materials around the lamp. In some instances, the lamp may crack. However, it rarely occurs in typical installations and is self-limiting. Once the lamp cracks and "goes to air" the arc extinguishes.

This type of lamp failure happens rarely in electronically ballasted T-12 or T-8 systems, but is more likely in T-5 and smaller-diameter lamp systems because higher lamp voltages are required and lamps have less mass to dissipate the heat. Electronic ballasts have now been developed that "sense" the impending end-of-life lamp condition and shut the lamp off until it is replaced. End-of-life sensing, while becoming a "standard" feature for new ballast designs, may still have to be specified to ensure its inclusion. Ballasts used with T-4 and T-5 lamps should have end-of-life sensing.

Electromagnetic (EM) Ballast Phaseout

It's clear that energy-efficient fluorescent lighting must involve high-frequency electronic ballast and lamp systems. Even the best state-of-the-art EM-ballasted systems will use more energy for equivalent light output. The reason is that at high frequencies, fluorescent lamps become approximately 10% more efficacious due to lower losses within the lamp itself. That improvement cannot be matched by EM ballasts operating the lamps on 60 Hz power. Recognizing this, the U.S. ballast industry, working with NEMA and the U.S. Department of Energy along with other lighting and energy stakeholders, have agreed on an almost complete phaseout of EM ballasts by 2010. Elimination of EM ballasts for new luminaires is set to occur by 2005. In states such as California, which have strong energy policies and practices and where the use of EM ballasts is already down to only about 5% of ballasts installed, it's expected that EM ballasts will disappear well before the scheduled dates.

6.5.4 Fluorescent System Application Considerations

Flicker

Electromagnetic ballasts are designed to condition the 60-Hz input power to the electrical requirements of the lamps. An EM ballast alters the voltage and current, but not the frequency. Thus, the light output of the lamp connected to the ballast is turned on and off 120 times each second. This oscillation of light or flicker is generally not noticeable unless the viewer is particularly sensitive, the light is seen in relation to another flickering object, like a computer screen or rotating object, or the light from only a single lamp is being utilized. Flicker can cause eyestrain and headache in sensitive individuals. Refer to section 2.2.6 for more about potential health effects of flickering light, and to section 4.3.2 for design guidance to reduce or eliminate flicker.

Electronic ballasts, on the other hand, pulse the lamp on and off many thousands of times each second, far beyond the capability of the eye to respond; therefore, no flicker is seen. But some electronic ballasts supply "modulated" high-frequency power to the lamp; this modulation frequency can sometimes be seen as flicker. If flicker is a consideration in a particular application, check the ballast manufacturer's specifications.

Audible Noise

An important benefit of electronic ballasts is the virtual elimination of audible ballast noise. Electromagnetic ballasts operating at 60 Hz generate audible noise due to the magnetic characteristics of the iron-core windings. Noise levels typically change for the worse as the ballast ages. In order to prevent misapplication, the ballast industry adopted a letter-based noise rating system of A, B, C or D, where A is the quietest. All electronic ballasts are A-rated for sound and should, if operating properly, emit no perceptible noise since any emissions are above normal human hearing frequencies.

Electrical and Building System Compatibility of Electronic Ballasts

Like virtually all lighting products, there are some applications in which high-frequency electronic ballasts may be incompatible with existing technologies. For example, there can be interference between electronic ballasts and the magnetic detector systems used in libraries to prevent theft. However, installation experience indicates that as long as electronic ballasts are at least 10 to 15 ft away from the detector units, problems with the detectors are unlikely to occur. A few other areas, such as medical equipment areas or elevator interiors, may also occasionally have equipment compatibility problems.

A second potential system compatibility problem with electronic ballasts may occur in conjunction with high-frequency power line carrier (PLC) control systems. The carrier frequency for PLCs usually ranges from 50 kHz to 200 kHz. These frequencies may be affected by one of the harmonic currents generated by electronic ballasts. The extent of this potential problem has not yet been fully researched. However, in simple PLC systems for residential applications when lighting and other appliances share the same distribution network, electronic ballasts may not be compatible. This may be resolved by the selection of a more appropriate frequency for the PLC system. In commercial systems where the PLC is isolated from the lighting circuits, problems may be minimal. If, however, the PLC is used to control the lighting system, the probability of problems occurring will increase.

IR Interference

In some instances, electronic ballasts can interfere with the IR signal from remote control devices. The result is that infrared remote receivers such as television sets may occasionally misinterpret or ignore commands. In the worst case, they may not respond to a remote controller at all except at a distance of a few feet or less. The following set of conditions can cause this problem: (a) electronic ballast operation in the region of 33–40 kHz; (b) a significant amount of infrared (in comparison to a single battery-driven LED); and (c) a large AC component in their radiant flux output. Compact fluorescent lamps reportedly cause more interference than linear fluorescents.

Possible compatibility problems posed by electronic ballasts arise only on rare occasions. These incompatibilities can usually be resolved or avoided and they shouldn't be used to disqualify electronic ballasts in other applications.

6.5.5 Application Guidelines—Linear Fluorescent Systems

Table 6-4 compares the initial and maintained values of new-technology linear fluorescent lamp systems to the obsolete electromagnetically ballasted T-12 system. T-8 systems are clearly an excellent choice, and T-5 systems may also be an excellent choice, depending on the system's cost and the lamp's thermal operating conditions. T-5 lamps are designed to emit their peak output about 10°C higher than T-12 or T-8 systems, with the idea that smaller lamps will be designed into smaller luminaires with more concentrated heat. The final decision as to which system is the most efficacious will, of course, depend upon the performance of that system in the luminaire and the environment into which it is to be installed.

Considering the above, here are some additional practical guidelines that apply to both existing linear and new fluorescent systems:

- Always consider electronic ballasts for routine maintenance replacements and renovations. See section 7.9 for more about lighting retrofit opportunities.
- Instant-start systems are slightly more efficacious than rapid-start systems (check ballast input wattage ratings). Consider operating F32T8 lamps at full output with instant-start ballasts to obtain maximum energy efficiency for dedicated (non-dimming) applications.
- Exercise caution when using instant-start lamp-ballast systems with occupancy sensors or other applications with rapid switching cycles. Refer to chapter 8 for details about control devices.
- Consider stepped multilevel electronic ballasts as an alternative to switching adjacent lamps in luminaires (tandem wiring).
- Consider the use of low ballast factor (less than 75%) electronic ballasts in aisles or other circulation areas where partial light output will suffice. Installation of low ballast factor ballasts is also a cost-effective solution for retrofitting spaces that are over-illuminated.
- Consider full-range (1% to 100%) dimming electronic ballasts for functional dimming requirements in applications such as boardrooms, conference rooms and residences.
- In most instances, electronic ballasts are manufactured in standard ballast housings. This allows for quick and easy replacement in existing luminaires and permits their use in already tooled new luminaires. To facilitate replacement, the wires on typical non-dimming electronic ballasts use the same color coding as magnetic ballasts.

See chapter 5 for examples of applications using linear fluorescent systems.

Table 6-4 – Lamp-Ballast System Comparisons for Linear Fluorescent Lamps, 2-Lamp Systems

Lamps	Initial Lumens /Lamp	Ballast Type[3]	Ballast Factor[4]	Lumen Output[5]	Input Watts	Efficacy Lm/W	Relative Input Watts	Relative Lumen Output	Relative System Efficacy	Lumen Maint. Factor– Mean Lumens	Mean System Efficacy Lm/W	Relative Mean System Efficacy
(A)	**(B)**	**(C)**	**(D)**	**(E)**	**(F)**	**(G)**	**(H)**	**(I)**	**(J)**	**(K)**	**(L)**	**(M)**
Two-Lamp Systems Operating in Open Air[1, 2]												
34 W F40T12/ES	2700	EEM	0.87	4698	72	65	Base 100%	Base 100%	Base 100%	0.86	56	Base 100%
4100K CW												
(CRI= 65)												
32 W F32T8	2800	EPRS	0.88	4928	61–64	77–80	85–88	105	118–123	0.95	73–76	130–136
4100K RE-70												
(CRI = 70+)		ERS	0.88	4928	62–63	78–79	86–87	105	120–122	0.95	74–75	132–134
		EIS	0.77–1.20	4312–6720	51–78	84–86	69–108	92–143	129–132	0.95	80–82	143–146
32 W F32T8	2950	EPRS	0.88	5192	61–64	81–85	85–88	111	125–131	0.95	77–81	137–145
4100K RE-80												
(CRI = 80+)		ERS	0.88	5192	62–63	82–83	86–87	111	126–128	0.95	78–79	139–141
		EIS	0.77–1.20	4543–7080	51–78	89–91	69–108	96–150	137–140	0.95	85–86	152–154
FT40W/2G11[6]	3150	EPRS	0.88	5544	74	75	103	118	115	0.9	67	120
4100K RE-80												
CRI = 80+		ERS	0.85	5355	71	75	99	114	115	0.9	67	120
		EIS	0.88–0.96	5544–6048	72–75	77–81	100–104	118–129	118–125	0.9	69–73	123–130
FT50W/2G11[6]	4000	ERS	0.98	7840	106	74	147	167	114	0.85	63	112
4100K RE-80												
FT55W/2G11[6]	4800	EPRS	0.98	9408	119	79	165	200	122	0.85	67	120
4100K RE-80												
(CRI = 80+)		ERS	0.84	8064	100	81	139	172	125	0.85	69	123
28WT5[2]	2600 (25°C)	EPRS	1.00	5200	62–66	79–84	86–92	111	122–129	0.95	75–80	134–143
4100K RE-80												
(CRI = 80+)	2900 (35°C)	EPRS	1.00	5800	62–66	88–94	86–92	123	135–145	0.95	84–89	150–159
54WT5/HO[2]	4450 (25°C)	EPRS	1.00	8900	118	75	164	189	115	0.95	71	127
4100K RE-80												
(CRI = 80+)	5000 (35°C)	EPRS	1.00	10,000	118	85	164	213	131	0.95	81	145

59 W F96T8/IS	5900	EIS	0.85–0.88	10,030–10,384	110	91–94	153	213–221	140–145	0.91	83–86	148–154
4100K RE-80												
(CRI = 80+)												
86WF96T8/HO	8200	EPRS	1.00	16,400	185	89	257	349	137	0.9	80	143
4100K RE-80												
(CRI = 80+)		ERS	0.88	14,432	160	90	222	307	138	0.9	81	145
75WF96T12/IS	6400	EIS	0.85–0.88	10,880–11,264	132–135	82–83	183–188	232–240	126–128	0.94	77–78	137–139
4100K RE-70												
(CRI = 70+)												

Notes:

1. These data are for comparison purposes only. For performance in actual luminaire systems, refer to information about LER (Luminaire Efficacy Rating) in section **7.1.2**.

2. Open air 25°C bare lamp tests as per ANSI C82.2. T-5 linear lamps are designed to peak at 35°C. T-5 data are shown for 25°C and 35°C.

3. Ballast abbreviations: EEM = Energy Efficient Magnetic; EPRS = Electronic Program Rapid Start (reduces cathode heating after starting); ERS = Electronic Rapid Start; EIS = Electronic Instant Start.

4. Ballast factors cited are typical of commercial ballasts available on the current market; use of other ballast factors will produce different results.

5. Lumen output based on initial (100 hour) rated performance.

6. Fluorescent twin, i.e., T-5 Twin-tube with 2G11 4-pin base.

6.5.6 Compact Fluorescent Lamps

Compact fluorescent lamps (CFLs) are defined as single-based fluorescent lamps of bent-tube construction. They are now made in ratings of 5–55 watts (roughly 250–3900 initial lumens) and can replace incandescent lamps in terms of light output up to 150 watts equivalent.

Developed in the late 1970s and introduced to the U.S. market in the early 1980s, the first models were designed to be used as retrofits for standard incandescent lamps. Integral lamp-ballast combinations with screw-in Edison bases provided convenient and inexpensive alternatives for lamps used in hotels, apartment complexes, schools, and other long burning-hour applications. Modular systems with replaceable lamps became popular as well. By the mid-1980s, however, manufacturers had introduced luminaires and systems designed for CFLs, including entirely new products that have led to the development of efficient and unique new luminaires.

Figure 6-20 – Examples of Compact Fluorescent Lamps
Photo courtesy GE Lighting.

Screw-base CFLs

Modular and integral compact fluorescent systems with Edison-screw sockets, while convenient and effective at upgrading existing incandescent sockets to a higher efficacy lamp, are generally not a good energy efficiency choice because of the risk of "snap back"—the practice of replacing a CFL with an incandescent lamp for reasons of cost or expediency.

Screw-base systems are also generally less efficient than dedicated lamp/ballast/luminaire systems that have been designed to work together optimally. For maximum energy effectiveness, specify and use only dedicated systems. Typically, these systems utilize 4-pin lamps. These will be the only CFL systems discussed in detail in the *Advanced Lighting Guidelines.*

Advanced CFL Products

Most compact fluorescent lamps are capable of generating about 50–60 lumens per watt, but are limited in lumen output by the “architecture” of the glass and base arrangement. Several manufacturers are now offering CFLs consisting of three (6) or four (8) bent tubes, as opposed to earlier twin-tube (2) and quad-tube (4) configurations. This allows the length of the assembly to be shortened for more lumens in a smaller overall package.

Additional CFL shapes have also been developed. A square-shaped "2D" configuration is now available in three sizes and five different wattages. Its thin compact shape make it suitable for low-profile surfaces, small recessed luminaires and torchieres. A flat “finger” lamp is also available for similar applications in three wattages and sizes.

One lamp manufacturer is now producing a T-2 diameter, sub-miniature, wedge-base fluorescent lamp in four lengths and wattages. As is the case with all compact fluorescents, these lamps use a rare-earth phosphor coating for good color rendering. T-2 lamp efficacy is 50–60+ lumens per watt, exclusive of ballast losses. Applications include task, sign and showcase lighting. Figure 6-21 shows an example of a T-2 lamp and electronic ballast.

Figure 6-21 – T-2 Lamp and Electronic Ballast
Photo courtesy OSRAM SYLVANIA.

CFL Lamp Range

The lamp types shown in Table 6-5 are offered by several manufacturers, except as indicated, and illustrate the configurations and ranges of wattages and light outputs generally available. Only 4-pin lamps are shown since these are the most efficacious types. Ballasts that operate these lamps are of the instant-start, rapid-start, step or dimming types. Color variations are not shown, but generally lamps are available in 2700, 3000, 3500 and 4100 Kelvin ratings, all with CRI of 80+. There are also a few lamps rated for 5000K. Life ratings vary somewhat by manufacturer. Most lamps are rated for 10,000 hours, with some type "FT" lamps rated at 12,000 or 20,000 hours (3 hours/start).

For general lighting applications, types "T" and "M" operated on high-frequency electronic ballasts offer high system efficacies, long life (typically 10,000 or 12,000 hours) and a broad range of light outputs that match standard incandescent lamps from (roughly) 60 to 200 watts

Table 6-5 – CFL Configurations, Wattages and Output Ranges

CFL Lamp Configuration	Wattage Range	Light Output Range (Initial Lumens)
Single Tube (Type "S")	5–7–9–13	230–400–580–825
Double Tube (Type "D")	10–13–18–26	600–900–1200–1750
Triple & Multiple (Types "T" & "M")	13–18–26–32–42	900–1200–1800–2400–3200
Fluorescent Twin (Type "FT")	18–24–36–40–50–55	1250–1800–2900–3150–4000–4800
2D (Proprietary Design)	10–16–21–28–38–55	650–1050–1350–2050–2850–3900
Flat (Type "F") (Proprietary Design)	18–24–36	1100–1700–2800
Circline T5 (HO)	22-40-55	1800-3200-4000

CFL Dimming and Switching

Four-pin CFLs operate in rapid-start or program-start mode on electronic ballasts, so CFL dimming ballasts operate as described in section 6.5.3 above. It's worth repeating, however, that, in general, compact fluorescent lamps can't be dimmed using dimming equipment designed for incandescent lamps. One device, designed for 4-pin lamps is an exception. This device, which must be used with a luminaire that includes a specific type of factory-installed ballast/adapter, will dim CFL lamps using incandescent wallbox dimmers. Refer to section 8.2 for more about dimming.

Amalgam Lamps

A recent CFL development is the use of amalgam technology to better control the light output of the lamp over a broad temperature range. Amalgams (mixtures of metals and mercury) optimize the amount of mercury vapor present in the arc discharge. Too little mercury vapor reduces lamp light output and efficacy; too much reduces output and causes the lamp to operate at less than rated watts. Figure 6-22 illustrates the light versus temperature performance difference between amalgam and non-amalgam lamps. Amalgam lamps may take slightly longer to warm up to full light output after initial turn-on.

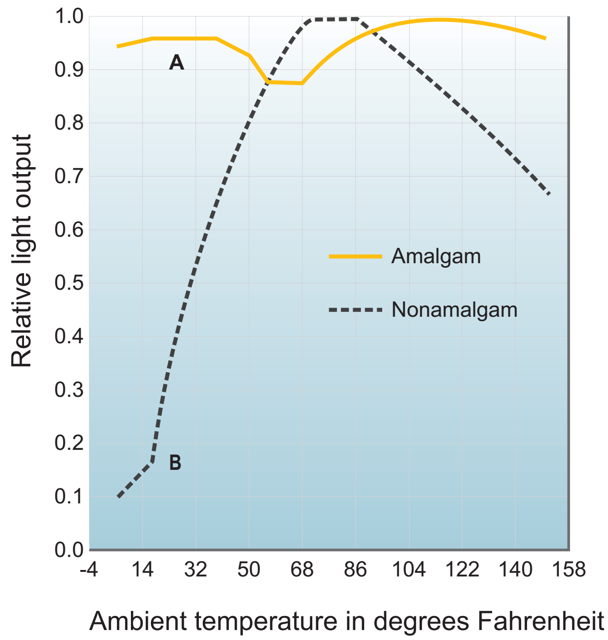


Figure 6-22 – Light Output vs. Temperature, Amalgam and Non-Amalgam CFLs
Source: IESNA Lighting Handbook, 9th Edition

Temperature and Burning Position

Figure 6-23 shows the typical performance of CFLs with varying ambient temperature and burning position for both amalgam and non-amalgam (mercury) designs. In applications where CFLs are mounted in small volume luminaires with a lack of air circulation (such as in lensed downlights), the user should expect the ambient temperature to be between 40°C and 50°C (104°F to 122°F), and should lower the lamp lumen rating accordingly, unless amalgam lamps are being used. Luminaires are discussed in detail in chapter 7.

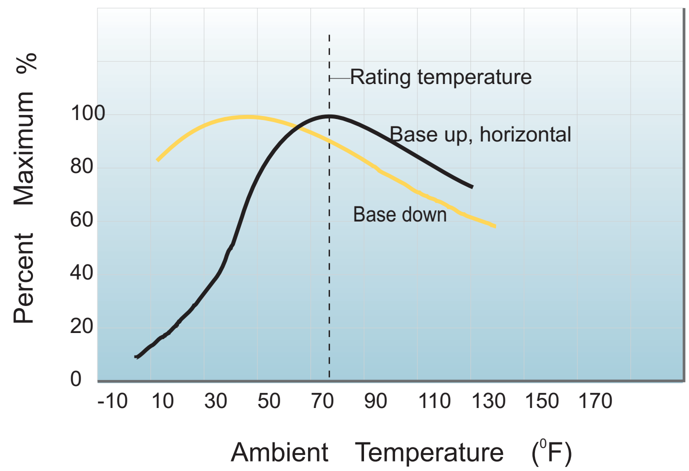


Figure 6-23 – CFL Output vs. Ambient Temperature & Burning Position
Source: IESNA Lighting Handbook, 9th Edition

CFL Nomenclature

As with linear lamps, lamp manufacturers tend to create marketable product names and identifications. These names may make for better marketing, but they also make it more difficult to write a generic specification. However, the National Electrical Manufacturers Association (NEMA) has developed a generic designation system for non-integral (externally ballasted) compact fluorescent lamps. In most cases the specifier can easily relate the desired lamp product to the NEMA code. The code consists of the following elements:

CF (Shape) (Wattage) / (Base Designation)/(Color)

The shape designator may be T (twin-tube), Q (quad-tube), TR (triple tube), S (square shape), or M for multiple or any configurations not covered by the other designators. Base designators are set up according to an international IEC/ANSI system and are readily available from lamp manufacturers' catalogs. An example using the NEMA generic designation code for a 32-watt, triple-tube lamp with a 4-pin base, 80+CRI and 3500K rating would be: CFTR32W/G24q/835.

T-5 twin lamps (not the linear T-5 lamps) use an "FT" prefix instead of the "CF."

6.5.7 CFL System Performance

As with linear lamps, CFL system efficacy depends on the ballast type used and the luminaire's thermal characteristics. Less important with the growing use of amalgam lamps is lamp burning position. Specifiers should still check luminaire photometric data, however, to determine whether or not the luminaire has been tested with mercury or amalgam lamps.

Table 6-6 lists several CFL systems and compares their open-air performance.

Table 6-6 – CFL System Performance

Generic[1] CFL Lamp Type	Rated Lamp Lumens (lm)	No. of Lamps	Ballast Factor (BF)	System Lumens	Ballast Input Watts (W)	Initial System Efficacy (lm/W)	Mean Rated Lamp Lumens	Mean System Efficacy (lm/W)
CFQ 13W	900	1	1.00	900	16	56	755	47
CFTR 13W	900	2	1.00	1800	29	62	(0.84)	52
CFQ 18W	1200	1	1.00	1200	20	60	1020	51
CFTR 18W	1200	2	1.00	2400	38	63	(0.85)	54
CFQ 26W	1800	1	1.00	1800	28	64	1510	54
CFTR 26W	1800	2	1.02	3670	55	67	(0.84)	56
CFTR 32W	2400	1	0.98	2350	35	67	2010	56
CFTR 32W	2400	2	0.96	4600	69	67	(0.84)	56
CFTR 42W	3200	1	1.00	3200	45	71	2690	60
CFTR 42W	3200	2	0.95	6080	94	65	(0.84)	55

[1]The full generic lamp designation includes a ""-/G24q"" to indicate the lamp base configuration; e.g., CFQ 13W/G24q plus a 3-digit color designation suffix.

Rated lamp life is 10,000 or 12,000 hours depending upon manufacturer and the specific lamp type.

6.5.8 Electrodeless Lamps

Five electrodeless lamp designs have been built and are available commercially. Four are low-pressure designs utilizing radio frequency energy to ionize mercury vapor similar to a fluorescent lamp; the other is an HID design utilizing sulfur and a high-temperature, high-pressure discharge. One of the low-pressure designs, developed in 1991, is available only in Japan. The three others are available in North America and are shown in Figure 6-24 through Figure 6-26 and listed in Table 6-7.

As the name suggests, electrodeless lamps operate without the usual cathodes inside the discharge tube. Since cathode deterioration is a prime determinant of lamp life and depreciation, eliminating cathodes inherently helps to keep the lamps operating longer at higher efficacies.

Figure 6-24 – Electrodeless Lamp Design
Closed magnetic core, ferrite toroid (donut shape). Photo courtesy OSRAM SYLVANIA.

Figure 6-25 – Electrodeless Lamp Design
Open magnetic core, integral ballast (reflector design). Photo courtesy GE Lighting.

Figure 6-26 – Electrodeless Lamp Design
Open magnetic core, separate ballast (globe design). Photo courtesy Philips.

Table 6-7 – Performance Characteristics of Electrodeless Low-Pressure Lamps

System Description	Operational Frequency	System Watts	Initial Lumens	Mean Lumens	Mean Efficacy (Lm/W)	Rated Life (Hours)
Closed Magnetic Core, Ferrite Toroid Donut Shape (Figure 6-24)	250 kHz	107	8000	6280	58.7	100,000
		157	11,000	8635	55	100,000
		157	12,000	9420	60	100,000
Open Magnetic Core, Integral Ballast Reflector Design (Figure 6-25)	2.5 MHz	23	1100	880	38.3	15,000
Open Magnetic Core, Separate Ballast, Globe Design (Figure 6-26)	2.65 MHz	55	3500	2800	50.9	100,000
		85	6000	4800	56.5	100,000

Two of the designs (closed magnetic core, and open magnetic core—separate ballast) are designed for long burning-hour locations where maintenance may be expensive or difficult and where substantial amounts of light are required (for example, roadway lighting, security lighting, signs, tunnels). The integral reflector design is designed to replace a 65–75 watt incandescent reflector flood lamp in downlighting applications.

6.6 HID Lamps

High-intensity discharge (HID) lamps are characterized by small, bright arc tubes made from quartz or translucent/transparent ceramic materials. These arc tubes contain electric discharges of vaporized metals operating at relatively high temperatures and pressures. There are three main types of HID lamps: mercury, metal halide (MH) and high-pressure sodium (HPS). HID lamps were once thought suitable only for limited outdoor or industrial lighting. However, improvements in color and efficacy, longer lamp life, and the development of low-wattage and compact lamps together with the introduction of suitable luminaires have expanded the use of HID lamps into commercial and even residential lighting applications.

HID lamps tend to be the most energy-efficient choice where the lighting design requires light sources with good optical control, high lamp efficacy, long life (tens of thousands of hours), insensitivity to ambient temperatures and good-to-excellent color.

Figure 6-27 – Examples of HID Lamps
Photo courtesy OSRAM SYLVANIA.

6.6.1 Technology Description

All HID lamps utilize a mixture of gases and metal vapors as the discharge elements in the arc tube. Arc tubes may be made out of quartz (see the sidebar About Lamp Glass, in section 6.4.2), which is strong, heat resistant and resists the chemical activity of mercury and the metal salts used in MH lamps. But quartz cannot contain the hot and corrosive sodium vapors needed for HPS lamps and so the development of HPS lamps hinged on the fabrication of a new arc tube material. High-purity aluminum oxide or, technically, "polycrystalline alumina" became the material of choice because of its high-temperature stability, strength and excellent light transmission characteristics. All HPS lamps utilize arc tubes of this alumina material and, more recently, such arc tubes have been employed for certain MH lamps as well. These lamps are designated by various trade names but the descriptions will include the phrase "ceramic arc tube metal halide" in some form.

HID Timeline

Mercury Lamps

Mercury lamps were first developed in 1901, but compact arc tube versions didn't appear until some 30 years later. They became widely used for roadway lighting after the development of long-life lamps in 1960 and began to be used for indoor general lighting after improved-color or "deluxe white" phosphors were introduced in 1966. The efficacy of mercury lamps that peaked at about 50 lumens per watt together with relatively poor depreciation characteristics have made the mercury lamp obsolete for energy-efficient lighting. It should not be used in new installations and existing installations should be upgraded to use a more energy-efficient source. Mercury lamps will not be discussed further in these guidelines.

Metal Halide Lamps

Metal halide (MH) lamps were originally developed in 1965 and marketed as "better than mercury lamps" since they were more efficient and provided white light for exterior and industrial lighting. Since that time the technology has expanded considerably to include lamps with a variety of types, shapes, wattages and colors suitable for nearly any lighting application. Efficacy varies by type and wattage, but ranges from 50 to over 100 lumens per watt. Metal halide lamps are discussed in detail in section 6.6.2.

High-pressure Sodium Lamps

High-pressure sodium (HPS) lamps were developed in 1961 and introduced commercially in the mid-1960s as energy-efficient sources for exterior, security and industrial lighting applications. HPS lamps rapidly found their ideal application niche in roadway lighting service as rated life increased from the initial 6000 hours to more than 24,000 hours. Most new roadway lighting continues to use HPS lamps. HPS lamps remain the most efficient of the HID lamp sources when comparing raw lumen output. They are best used in applications where good color rendering is not a crucial concern or social interactions are not important. High-pressure sodium lamps are discussed in detail in section 6.6.3.

Lamp Starting and Restrike

It's not possible to instantly ignite a cold general-lighting HID lamp to full brilliance. When the power is switched on, HID lamps start in a "glow" state or at very low output. Heat from the arc increases the arc tube temperature, causes the internal gas pressure to build and the metal compounds to melt and vaporize. As these gas mixtures enter the arc, they are ionized and emit energy. Starting the arc initially may take a few seconds and the duration of the warm-up period can range from 2 to 10 minutes depending on the lamp and ballast characteristics. Lamp light output and color will change dramatically during this time.

If electrical power is interrupted, even briefly, an HID lamp will extinguish. The lamp must then cool down before the arc can restrike. Lamp restrike periods vary—again depending on lamp and ballast type—and can last from 1 to 15 minutes.

In situations where the restrike period could create hazardous conditions, temporary supplementary lighting using fluorescent or halogen lamps is usually installed. Such systems may be built into the HID luminaire and the switching handled automatically. Some MH and HPS luminaires can also be specified with "instant restrike" capability. A special ballast or circuit developing very high voltages is required to instantly restrike a hot HID lamp, but such systems are a good solution in applications where there are frequent momentary power failures or voltage dips.

For HPS systems, there is another alternative involving a special lamp with a second arc tube connected in parallel with the one in operation. Only one arc tube can operate at any given time, so in the event of a momentary power failure, the "cool" arc tube begins to operate immediately when power returns. In practice, the lamp will start at about 10% of its full light output and will reach full output in approximately 90 seconds since the "cool" arc tube is in close proximity to the operating arc tube and therefore partially warmed up. Figure 6-28 shows a dual arc tube HPS lamp.

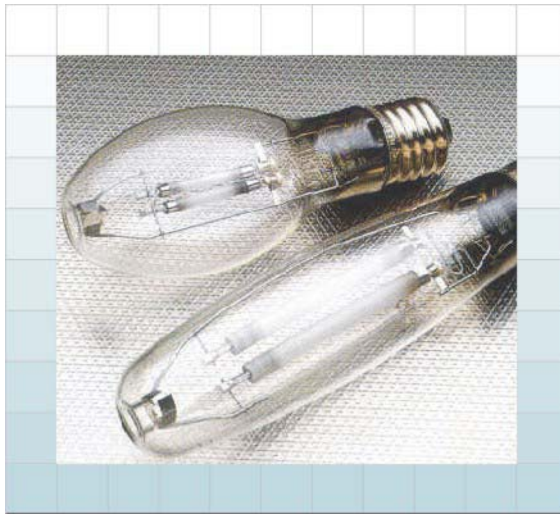


Figure 6-28 – Dual Arc Tube HPS Lamp
Photo courtesy GE Lighting.

MH lamps that operate on standard MH ballasts with no auxiliary starting circuits contain three electrodes. Two main electrodes are mounted at the ends of the arc tube. At one end, an auxiliary or starting electrode is mounted next to the main electrode. The lamp begins the starting process when the gas between the main and starting electrode ionizes. After starting, a thermal switch in the lamp disables the starting electrode. Unlike standard metal halide lamps, HPS lamps and the newer "pulse start" MH and ceramic arc tube MH do not contain starting electrodes. Starting is initiated via an external high-voltage pulse circuit matched to the ballast characteristics. The system used for HPS lamp starting results in warm-up and restrike periods that are much shorter than those of metal halide lamps. A 150-watt HPS lamp, for example, will cool down, restrike and warm up again after a momentary power interruption in about 2 minutes.

Lamp Life and Failure Modes

- *Metal Halide:* Depending on the lamp type, failures are due to cathode deterioration and the subsequent blackening and failure of the arc tube or seals, or the loss of sodium through the wall of the quartz arc tube. Arc tubes in lamps that are burned continuously are more likely to rupture at end-of-life; manufacturers recommend that such systems be turned off at least once a week to minimize the chances of such failures.
- *Standard High-pressure Sodium:* Loss of sodium through the ceramic wall of the arc tube causes the operating voltage of the lamp to rise beyond what the ballast can supply. The lamp then "cycles" on and off as the ballast tries unsuccessfully to maintain the arc. The arc tube seals can also crack and leak sodium into the space between the arc tube and outer bulb of the lamp.
- *Low-mercury HPS Lamps*: These "unsaturated" HPS lamps drop significantly in light output when their sodium is lost and then signal their end-of-life status by either going out or shifting to a blue color (depending upon design) similar to clear mercury lamps (see Unsaturated HPS Lamps in section 6.6.4). They do not cycle as do conventional HPS lamps.
- *No-mercury HPS Lamps*: Xenon may be substituted for mercury vapor as a buffer gas so that the arc tube of these HPS lamps contains only xenon and sodium. Xenon, however, shifts the chromaticity of the discharge toward the green so the color appearance of these lamps does not match other types of HPS lamps and they should not be mixed.

6.6.2 Metal Halide Lamps

Wattages of metal halide lamps range from 32 to 2000 watts. A large number of envelope and base configurations are available. Major variations of metal halide lamps include:

- Universal-burning-position lamps that are relatively insensitive to lamp physical orientation
- Position-specific lamps that have maximum efficacy and lamp life
- Clear or phosphor-coated lamps ranging from 3400–4100K in chromaticity
- Optional warm (3000K) and cool (6500K) lamps in some sizes
- A few warm (3000–3200K) clear lamps, especially in lower wattages
- Lamps for open luminaires with internal arc rupture shields (see section 7.5 for luminaire information)
- Silver-bowl lamps that minimize glare and light trespass from directional luminaires
- Compact lamps without outer glass envelopes that produce a brilliant, high color rendering light in a comparatively small arc tube

Figure 6-29 shows various MH lamp configurations.

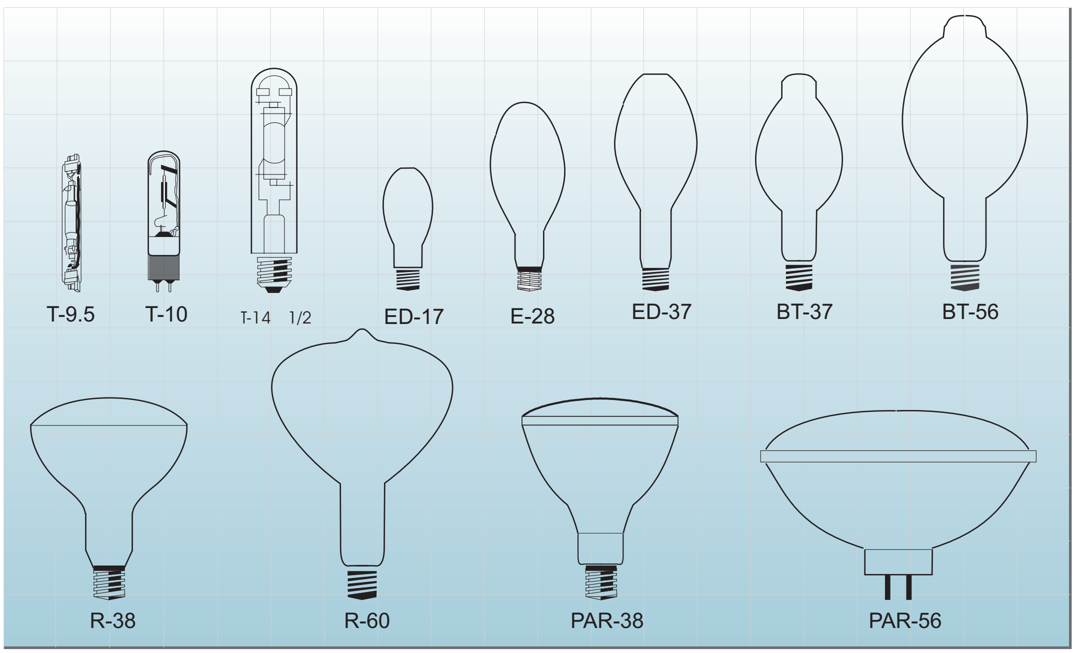


Figure 6-29 – Metal Halide Lamp Configurations

Universal-burning Position

Because of their ability to be burned in any operating position, the "universal" metal halide lamps are the most easily used. However, they perform best (maximum light output and life) when the arc tube is within about 15 degrees of vertical position. They are also typically less efficacious than lamps optimized for limited burning positions.

Lamp color choice with universal metal halide lamps is generally limited to standard clear (4000–4500K, 65 CRI) or coated (3700–4000K, 70 CRI). Recent improvements include the addition of more wattages, as well as the development of medium-based compact lamps. These lamps operate on ANSI standard ballasts and generate 65–100 lumens per watt.

Vertical- or Horizontal-burning Position

In addition to universal-burning-position products, metal halide lamps are also available that are designed to operate either vertically or horizontally. When designed for a specific burning position, metal halide lamps can generate more light and offer more color options than are available with universal-position lamps.

Vertical-burning

The vertical-burning metal halide lamp is optimized for base-up, base-down, or base-up/base-down operation, primarily for use in downlights. In addition to standard clear (4000–4500K) and coated (3700–4000K) lamps, warm color (2700–3200K) clear and coated lamps are available in various wattages. The newest products tend to have lower wattages with medium bases and smaller envelopes. One product—the 32-watt lamp—is designed specifically (and only) for operation on an electronic ballast. A principal advantage of vertical-burning lamps is efficacy. Lamps generate 70–110 lumens per watt, or about 10% more than universal-burning lamps. Table 6-9 provides performance information for vertically burning pulse-start metal halide lamps.

Horizontal-burning

As in vertical-burning metal halide lamps, optimum lamp design in horizontal lamps is achieved when operating position is predetermined. Horizontal high output or "super" lamps may have bowed arc tubes, and use a position-fixing pin in the base, called a prefocus or position-orienting mogul (POM) base. This base and matching socket assure correct positioning of the lamp.

Since these lamps are primarily used in outdoor lighting—floodlighting and highway signs are two major applications—the smallest wattage product available is 175 watts. The most popular metal halide lamp colors are offered (3200K coated, 3700K coated, and 4100K clear). As with vertical lamps, efficacy is 70–110 lumens per watt.

Color Shift

It is characteristic of metal halide lamps to shift in color both between lamps and over time. As metal halide lamps operate, the circulation of hot gases in the arc tube, the area and position of the "pool" of molten halides, lamp temperature and age all contribute to a continuously changing mixture of halides and their moment-to-moment light and color output. Unfortunately, the most likely lamp color characteristic to change is chromaticity, which is also the most visible to the eye.

There are, however, several strategies that can minimize lamp color shift so that MH lamps can be used as energy-efficient alternatives to incandescent and fluorescent light sources. Further, lamp manufacturers have struggled with the problem and are beginning to achieve some success, which is apparent with the newer pulse-start and ceramic arc tube products.

There are a number of strategies for minimizing lamp color shift:

Specification Considerations

- Determine what color shift is acceptable for the application and if the acceptability applies to the overall appearance of the lamps over time or the lamp-to-lamp variation at any given time. Recognize that the color stability of metal halide lamps is not expected, at least in the near term, to be the same as that of incandescent and fluorescent lamps.
- Consult with the lamp manufacturer to determine what variation can be expected and what variation might be put into writing as a warranty of performance.
- Ask lamp and ballast manufacturers about lamp/ballast systems that work together to minimize color shift and variation. Some electronic HID ballasts now have sensing and feedback circuitry that helps to stabilize lamp operation.
- Use the same ballast model throughout the installation.
- Choose ballasts with good regulation characteristics, especially if the supply voltage is subject to voltage variations.

- Specify newer-technology lamps. Lamps with "shaped" arc tube chambers, pulse-start technology and ceramic arc tubes are designed to have minimal color shift characteristics.

Installation and Operation Considerations

- Before judging the color of new lamps in an installation, burn the lamps for at least 100 hours to stabilize the lamp color characteristics.
- If lamps have been moved, and particularly if the lamps have been tipped or shaken when warm, they must be re-stabilized. Operate them for several hours in their new positions.
- Operate all of the lamps in an installation in the same burning position.
- Do not operate metal halide lamps on a dimmer.
- If lamp-to-lamp color variation over time is an important issue, specify group relamping. Lamp manufacturers may select lamps with matching color values on request or at extra cost for critical installations.
- In general, operate lamps with quartz arc tubes vertically. Off-vertical positions are more likely to change the surface area of the halide "pool."

Double-ended Lamps

Double-ended metal halide lamps in compact packages (without enclosing outer glass envelopes), illustrated in Figure 6-30, were originally introduced in Europe and have been very successful there. Some manufacturers produce these lamps with special halide chemistries, resulting in lamps with very high CRIs of 80 or more. These lamps operate in the range of 65–95 lumens per watt, and the 70-watt lamp with electronic ballast achieves a system efficacy of about 75 lumens per watt, over 10% more than with magnetically ballasted operation. Moreover, the reduced ballast package lends itself to smaller luminaires including track lighting equipment.

Double-ended lamps must be operated with the arc tube within 45 degrees of horizontal.

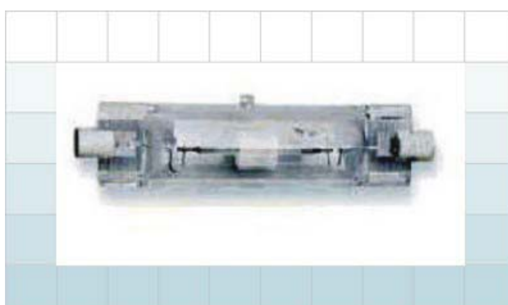


Figure 6-30 – Double-Ended HID Lamp
Photo courtesy GE Lighting.

Open-luminaire (Protected) Lamps

Most metal halide lamps require enclosed luminaires to protect people and property in the event of lamp rupture and, in the case of single-envelope lamps, high levels of UV emissions. Although rare, metal halide arc tubes can fail—especially near end-of-life if the lamp has been burned continuously.

However, a few metal halide lamps are listed for use in open luminaires. These are typically indicated in the "notes" column of manufacturers' catalogs. One type is simply a lamp design tested by the manufacturer determined to have a failure risk of virtually zero. Another type is called a protected lamp. These lamps typically employ an inner glass shield or reinforced arc tube so that, in the event of arc tube failure, the pieces are contained within the lamp's outer envelope. Protected lamps have a special base design. If the open luminaire is equipped with the matching exclusionary lampholder, non-protected lamps cannot be installed.

Of course, the best protection is the use of an enclosed luminaire, especially if lighting maintenance procedures are such that there is a significant chance that a non-protected lamp could be installed. Protected and non-protected lamps are electrically interchangeable; the use of exclusionary lampholders will prevent mechanical interchangeability.

Protected lamps are usually designed for universal or vertical burning. They are rated slightly lower in lumen output compared to standard vertical burning lamps.

Table 6-8 – Summary of Open and Enclosed Luminaire Options, Metal Halide Lamps

Luminaire	Socket	Lamp
Open	Exclusionary	Protected design (arc tube enclosed in a quartz shroud meeting ANSI test criteria)
Open	Standard	Standard, but approved by the manufacturer for open luminaires
Enclosed	Standard	Any

Instant-restrike Lamps

Double-ended and specially designed double-envelope metal halide lamps may be restarted instantly if used with special ballasts and luminaires. Typical applications are high-security floodlighting and televised professional sports lighting where the chance of loss of light is intolerable. By building the lamp, ballast and socket to withstand extremely high voltages (up to 30,000 volts), MH lamps can be reignited "hot," returning to full light output in seconds. Designed for higher wattage lamps, such as 1500 and 2000 watt, instant-restrike systems utilize high-voltage wiring, sockets and ballast construction.

Directional Metal Halide Lamps

Metal halide arc tubes in the familiar R and PAR lamp envelopes provide MH efficacy inside a compact reflector enclosure, an alternative to incandescent PAR and R lamps. See Figure 6-31. PAR wattages available include 39-watt PAR-20; 39- and 70-watt PAR-30; 70-, 100- and 150-watt PAR-38; and 150- or 1000-watt PAR-64. Metal halide PAR-38 lamps are an especially good tool for use in track lights, landscape lights and retail store display applications.

Figure 6-31 – Directional Metal Halide PAR-38 Lamp
Photo courtesy GE Lighting.

Pulse-start Lamps

Eliminating the third starting electrode from metal halide lamps improves lumen maintenance, color stability and life (according to ratings from one manufacturer, lamp life may increase from 10,000 to 15,000 hours). Lamp efficacy remains about the same. The lamp starting requirements have not changed, however, so some means to start the lamp must be provided. Pulse-start lamps are designed to use an external starting circuit. Such circuits are either integrated into the ballast or included as a ballast add-on. Performance information for pulse-start lamps is shown in Table 6-9.

Table 6-9 – Performance of Pulse-start Metal Halide Lamps
Clear Lamps, Vertically Burning, Enclosed Luminaires

Lamp Watts	Chromaticity/CRI (Kelvins/Ra)	Initial Lumens	Mean Lumens	Rated Life(Hours)	Mean Lm/W
50	4000/65	3400	2550	10000	51
70	4000/65	5600	4200	15000	60
	3200/65	5600	4200	15000	60
100	4000/65	9000	6800	15000	68
	3200/65	9000	6800	15000	68
150	4000/65	15000	11300	15000	75
	3200/65	15000	11300	15000	75
175	4000/75	17500	14000	15000	80
	3200/65	16250	12500	15000	71
250	4000/65	21500	16200	15000	65
400	4000/65	44000	33900	15000	85
	3200/65	44000	33900	20000	85

Ceramic Arc Tube Metal Halide Lamps

Substituting alumina ceramic arc tubes for the traditional quartz arc tubes in metal halide lamps simplifies the arc tube structure and makes possible excellent color warm-toned (3000K) lamps with improved color stability. Manufacturers publish "lifetime" chromaticity shifts of +/- 200K with CRI ratings of 80–85. These are two-cathode pulse-start designs with initial lamp efficacies of 85–90 lm/W. Available wattages include 39, 70, 100 and 150 watts, in double-ended, single-ended and PAR configurations. Ceramic arc tube MH lamps are excellent energy-saving alternatives for halogen incandescent PAR, R and MR lamps.

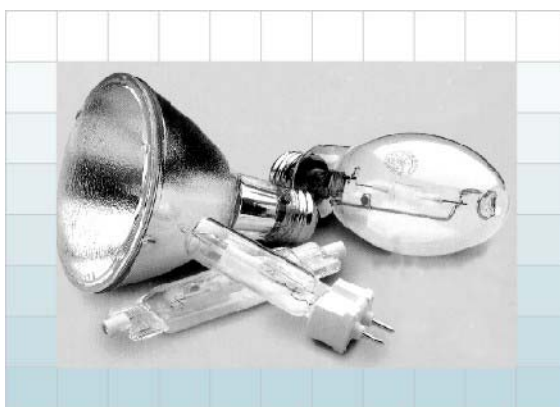


Figure 6-32 – Ceramic Arc Tube Metal Halide Lamps
Photo courtesy GE Lighting.

6.6.3 High-pressure Sodium Lamps

Standard Lamps

HPS lamps, unlike most metal halides, don't require enclosure except to prevent moisture from accumulating on the lamp. This makes HPS lamps especially easy to use in many luminaire types.

Moreover, the virtual insensitivity of HPS lamps to operating position means that fewer lamp types are needed compared to metal halide.

Lamp color temperature in HPS lamps doesn't vary much. While the deluxe HPS lamp has a relatively high CRI (65) for HPS technology, its color temperature of 2100–2200K is not much different from standard HPS, which varies between 1900K and 2100K. All HPS lamps appear golden or golden-pink in color, and are not recommended for non-industrial interior lighting. HPS lamps are offered in many wattages. Lumens per watt, ranging from 70 to 120 (including ballast), increase with wattage.

Some HPS lamps can be obtained with two arc tubes. These so-called "standby" lamps are not only a reasonable alternative to some instant restrike requirements (described in section 6.6.2 above), but they also offer extended lamp life (when one arc tube no longer starts, the other takes over). One manufacturer now rates life as "double the life of single arc tube lamps"; others quote values up to 40,000 hours.

6.6.4 Advanced HPS Products

HID lamps are available in a wide variety of sizes, shapes and bases. HID lamp technology development is a continually evolving process, as manufacturers try to design lamp configurations and characteristics to meet an ever widening range of applications.

PAR and R Types

PAR and R-configured HPS lamps are useful as compact directional light sources—especially for outdoor lighting. The relatively poor color rendition of these lamps, however, limits their usefulness to specific industrial and security floodlighting and general lighting applications.

Double-ended HPS Lamps

The double-ended HPS lamp was designed for situations where enhanced optical performance is required and to take advantage of luminaires and lighting installations originally designed for the double-ended metal halide lamp. The double-ended HPS lamp offers comparable lumen output and performance to single-ended lamps.

Unsaturated HPS Lamps

This is a generic term for what lamp manufacturers are calling low-mercury or reduced-mercury HPS lamps. The design is intended to make the lamps non-cycling. They may also meet mercury disposal requirements for non-hazardous waste (see section 3.2.3). By limiting mercury, which makes up the sodium-mercury amalgam in the arc tube, unsaturated lamps do not go through the usual cycling process at end-of-life; rather they change to a blue color as the sodium is depleted or simply go out. Life and light output ratings are the same as for standard HPS lamps.

Mercury-free HPS Lamps

A further step in the effort to eliminate mercury from lamps is the mercury-free HPS lamp. Such lamps are designed to directly replace standard HPS lamps, but life, light output and lumen maintenance are slightly below the performance levels of the standard products.

Will This HID Lamp Work in That Luminaire?

How interchangeable are HID lamps and ballasts? Usually the question arises from the desire to use an existing luminaire and ballast, but to upgrade it to a more-efficient or longer-lasting HID lamp. Here are some general rules:

• HID interchangeability is limited even though lamps usually have either mogul or medium screw bases that physically fit into just about any luminaire. In reality, very few interchangeability options exist and those that do (typically involving such arrangements as operating HPS lamps on older mercury ballasts or certain MH lamps on HPS ballasts) result in system performance compromises. Expect less than optimum system efficacy and shorter life ratings compared to dedicated systems.

• For those situations that do work, similar lamp wattages must be involved. There are no interchangeable combinations that allow the use of low-wattage lamps on high-wattage ballasts and vice versa. For example, there is a 360-watt HPS lamp designed to be used on 400-watt mercury lag or reactor ballasts. Note that this particular combination is rated for 16,000 hours lamp life (rather than the usual 24,000+) and a mean lamp efficacy of 91 lm/W (versus the usual 113 lm/W).

• An exception is reduced wattage metal halide lamps designed specifically to operate on existing ballasts. There are 150-, 225- and 360-watt lamps available to operate respectively on 175-, 250- and 400-watt standard metal halide ballasts, with similar performance to the full wattage lamps.

• Use only lamp/ballast combinations recommended by the lamp and ballast manufacturer. These are typically shown in lamp manufacturers' literature.

• Note carefully any requirements to use enclosed luminaires if metal halide lamps are involved.

• In some cases, luminaires may be upgradeable to newer-technology lamps by using ballast kits. These are usually offered by a ballast or luminaire manufacturer. There are cautions, however, since sockets or luminaire optics may also require modifications.

• Check out advanced technology electronic HID ballasts. Some newer models are designed for multiple lamp types and may be available with automatic lamp sensing and input voltage sensing features.

Refer to chapter **7** for detailed information about luminaires and their appropriate applications.

6.6.5 HID Ballasts

Ballasts for HID lamps must perform the usual functions of starting the lamp and regulating the power flow during lamp warm-up and operation, but the growing sophistication of metal halide and high-pressure sodium lamps has complicated those original tasks to the point that the traditional electromagnetic "core and coil" designs are now giving way to electronic/electromagnetic hybrids and even to completely electronic ballast systems as a way of achieving optimum lamp performance over life. Features similar to those being added to fluorescent electronic ballasts are also appearing in HID offerings, such as automatic sensing of input voltage, multilamp operation and the ability of a single ballast to operate lamps of different wattages via automatic or manual settings. HID lamps do not become significantly more efficient when operated on high-frequency power, so electronic HID ballasts typically operate the lamp at the usual 60 Hz.

When HPS lamps were developed, lamp life was found to be dependent upon the ballast being able to compensate for the changes in lamp electrical characteristics as the lamp burned. In typical systems, due to changes in lamp voltage over time, HPS lamps initially operate at less than rated watts, then lamp watts increase to above rated values and finally, as the lamp approaches end-of-life, lamp watts again fall below rated values. That makes HPS ballast circuits somewhat more costly and complicated. Added to that was the need to have a high-voltage pulse applied to the lamp for starting. Now, of course, pulse-start metal halide lamps also require a starting pulse so both HPS and metal halide ballasts must have starting ignitor circuitry.

Depending upon the lamp, the best match between the power system, the ballast and the HID lamp for a given application therefore requires consideration of:

- *Lamp watts and nominal line voltage.* Determines the basic size, weight and circuit type of the ballast.
- *Variation of the line voltage.* How does the voltage available to the ballast change during the operating period? Determines the ballast "voltage regulation" characteristics required.
- *Input voltage "dip" tolerance.* Transient changes in the input voltage that may cause the lamp to extinguish.
- *Power factor requirements.* Affects building power quality, system load and utility costs.
- *Lamp wattage regulation.* How well does the ballast control the power flowing to the lamp and therefore the lamp light output?
- *Ballast losses.* Affects luminaire temperatures, system efficiency and therefore operating costs.
- *Line current (starting and open circuit).* Especially important during lamp warm-up when ballasts may draw higher than average current. The electrical system must be sized to handle the maximum current and only a certain maximum number of ballasts can be used per circuit.
- *Current crest factor.* Defined as the ratio of the peak lamp current to the root-mean-square (rms) value. Values of 1.4 to 1.6 are ideal. Higher values negatively affect lamp depreciation and life.
- *System operation* when there are rare or abnormal conditions such as a short circuits or momentary power interruptions or when the lamp reaches end-of-life.

6.6.6 Application Guidelines

HID Lamp Dimming

While it’s technically possible to dim some HID lamps, the results are not likely to be satisfactory from either a functional or energy-saving standpoint. HID lamps are designed to be operated only at full power and output. Anything less compromises performance—usually efficacy, life and color. For example, a metal halide lamp can be dimmed to about 50% of full power, but at this level it generates only about 25% of its rated lumens, and it will change color in an undesirable manner. HID dimming requires specialized ballasts and dimming electronics. Specifiers should carefully evaluate proposed systems with respect to warrantee responsibility in case of system performance problems.

An exception is the step-dimming (hi-lo) systems for HPS and MH lamps. These systems provide full light then switch to a lower standby level via a special circuit in the HID ballast. They are typically supplied by the HID ballast manufacturer and can be linked to manual or automatic controls for use in warehouses, parking areas and other installations where continuous high-level lighting is not required. Standby levels of about 50% (input power) are typically available. Since, for the low setting, the HID lamp is already on, lamp warm-up times after switching to full output are relatively short. See section 8.1.3 for more about hi-lo dimming systems.

Primary Applications

HID lamps are compact sources that lend themselves to projection and floodlighting situations, as well as to general illumination. They are best suited to interior applications where lamp burning hours are long. Examples include manufacturing, corridor, and display lighting, as well as commercial area lighting. Some of the best applications for HID lamps involve exterior lighting. HID sources are especially well suited to roadway, landscape, parking lot, security, and sports lighting, and architectural floodlighting. Table 6-10 compares the performance of HID lamps.

Table 6-10 – Performance Comparison of HID Lamps
Clear Single-Ended Lamps, Vertically Burning, Enclosed Luminaires

Lamp Watts	Chromaticity/CRI (Kelvins/Ra)	Rated Life (Hours)	Initial Lumens	Mean Lumens	Ballast Input Watts (120 V)	Mean System Lm/W
Pulse-start Metal Halide						
50	4000/65	10000	3400	2550	65 (M)	39
70	4000/65	15000	5600	4200	90 (M)	47
					78 (E)	54
100	4000/65	15000	9000	6800	127 (M)	54
					110 (E)	62
150	4000/65	15000	15000	11300	190 (M)	60
					168 (E)	67
175	4000/75	15000	17500	14000	208 (M)	67
250	4000/65	15000	21500	16200	288 (M)	56
400	4000/65	15000	44000	33900	448 (M)	76
Ceramic Arc Tube Metal Halide						
70	3000/82	10000	6200	4960	90 (M)	55
					78 (E)	64
High-pressure Sodium						
70	1900/22	24000+	6400	5450	91 (M)	60
100	2000/22	24000+	9500	8550	115 (M)	74
100	2700/85 ("White")	10000	5200	4430	120 (Hybrid)	37
	2200/60	15000	7300	6570	115 (M)	57
150	2000/22	24000+	16000	14400	170 (M)	85
250	2100/22	24000+	28000	27000	295 (M)	92
400	2100/22	24000+	51000	45000	457 (M)	98
1000	2100/22	24000+	140000	126000	1100 (M)	115

Notes: (E) = Electronic ballast (High Power Factor) (M) = Electromagnetic ballast (High Power Factor)

Special Application Considerations for HID Lamps

There are several precautions to consider when using HID lamps in certain situations. Manufacturers' literature on this subject is extensive, and troubleshooting guides, and engineering and technical bulletins are available. Some of the most important considerations are noted here.

- *Backup lighting.* In HID applications where a brief power outage could cause hazardous conditions or a major manufacturing shutdown, and where no backup non-HID emergency lighting system is in place, it's a good idea to specify that some portion of the luminaires be furnished with either instant-restrike or quartz backup lamps. This ensures that some type of backup lighting is in place until the HID lamps can be reignited.
- *Strobe effects.* All HID lamps are turned on and off 120 times per second in synchronization with the 60-Hz alternating current power supply, both with electromagnetic and typical electronic HID ballasts. Because of this, the use of HPS lamps in general lighting luminaires near rotating machinery may produce a stroboscopic effect, making the machinery appear to be motionless, a potentially hazardous situation. This can occur when the moving object rotates at any speed that is a multiple of 60 (for example, 2400 revolutions per minute). Strobe effects of this type can be mostly eliminated by the proper phasing of the luminaire power supply circuits, so that none of the machinery is lighted solely by luminaires on the same phase circuit.

HID Lamp Nomenclature

Specifications of HID lamps generally follow a designation system authorized and determined by ANSI. These designations begin with a letter (M for metal halide, S for HPS), followed by an ANSI number identifying the electrical characteristics of that lamp's ballast. After the number, there is a letter-number combination to designate the lamp envelope shape and size (ED-17, BT-28, etc.). Optional added designations may include base type, wattage, clear or coated, warm or neutral color, and/or standard or deluxe color rendering.

For instance, a 70-watt, double-ended, metal halide warm (3000K) colored lamp with deluxe color rendering could be designated as:

M85/T7/RSC/70/WDX

Similarly, a standard 250-watt, mogul-based, ellipsoidal-shaped HPS lamp with diffusing coating might bear the following designation:

S50/E28/MOG/250/COATED

There are important and popular HID lamps for which ANSI designations are still pending. This is true for many of the more recent lamp developments such as compact and pulse start metal halide lamps. In these cases, it may be necessary to use a proprietary specification to designate acceptable lamp and ballast manufacturers.

6.6.7 Low-pressure Sodium Lamps

An older variant of lamps using sodium as the primary light-emitting material is the low-pressure sodium (LPS) lamp. Constructed more like fluorescent lamps than HID lamps, LPS lamps are not widely used, but operate at higher efficacies than either fluorescent or HID sources and have relatively good performance characteristics, including rated lamp lives of 18,000–20,000 hours. Major drawbacks are their relatively large physical size (again, more like fluorescent lamps), difficult-to-control optics and a monochromatic color (CRI = 0). The latter limits their application to security, roadway, tunnel and similar applications where color rendering and appearance are not of concern.

LPS lamps are a preferred light source for outdoor lighting within the light-controlled perimeters of astronomical observatories because their narrow-band spectral emissions can be easily filtered out of telescope images and other astronomical sensing devices. They are not advanced sources in terms of the *Advanced Lighting Guidelines*—there have been few technology improvements in recent years. But they do represent energy-efficient lighting practice where their unique characteristics can be utilized.

Figure 6-33 – Low-pressure Sodium Lamps
Photo courtesy GE Lighting.

6.7 Light-emitting Diodes (LEDs)

LEDs are solid-state electronic devices that generate light via the transformation of electric energy to radiant energy within the crystalline structure of a semiconductor material (Figure 6-34). Electrically, LEDs act as diodes allowing current to flow in only one direction.

LEDs are physically small (the light-emitting element or "chip" is a fraction of a millimeter in size) and they are typically "packaged" like other solid-state devices in small plastic enclosures. A common package for a single LED is a T-1 ¾ capsule (about 5.6 mm).

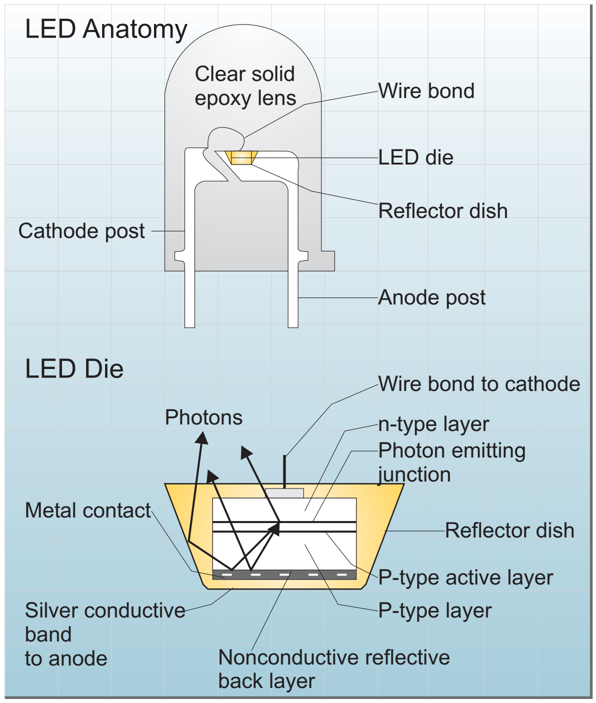


Figure 6-34 – Construction of an LED
Source: Sacramento Municipal Utility District

The types of semiconductor materials used for the chip determine the color and performance of the LED. Several colors have now been developed ranging from blue, blue-green, green and amber through orange, red and, more recently, white. Red, green and amber LEDs have been used for some time as indicator lights and in certain sign and display-screen applications. Blue LEDs are relatively new. Materials improvements continue to be directed toward expanding the range and efficacy of the various colors and the development of UV-emitting types.

The light output of an LED directly from the chip is "narrow band," which means that LEDs inherently emit more like a line source than a continuous source in the visible spectrum. Broader spectrum colors can, however, be generated through the use of phosphors excited by LED chips that emit blue light. White light LEDs are of two types: one type uses phosphors that absorb blue light and re-emit it as white light. The second type utilizes an arrangement of several chips emitting in the red, green and blue. The individual colors mix in the assembly so the resulting light output appears white. The first approach is currently favored by users and manufacturers because of cost and because phosphors emit broad-band white light and there can be some leeway in designing LEDs with different chromaticity and color rendering ratings. Color shift over time is also minimal. The phosphors currently available, however, are not as efficient as the phosphors used in fluorescent and HID lamps which have long been designed to absorb short-wavelength UV. White light LEDs using chip combinations may show initial color differences due to manufacturing variations. Color will shift over life as well since the output levels of the various chips degrade at different rates.

6.7.1 Operational Characteristics

LEDs operate on low-voltage direct current—the original designs were rated for 1.5 to 4 volts at a current of 20 mA. Newer "high-brightness" or "high current" designs may operate at 100 to 200 or more mA. Forcing more current through an LED makes the LED emit more light, but the additional power may also raise the temperature of the semiconductor material and accelerate the deterioration rate of the device which, in turn, reduces the light output of the LED long-term— much like the lumen maintenance characteristics of conventional lamps.

6.7.2 LED Performance

Life Ratings

LED life, like the life of other solid-state electronic devices, is expressed in terms of mean time between failures (MTBF). Translated into lighting industry terms, the "rated" life of LEDs is extremely long, perhaps as much as 50,000–100,000 hours; however the useful or "service" life may be shorter based on light output depreciation. Tests conducted in 1999 on white light LEDs available at that time, for example, indicated that the service life of the devices tested would be less than 10,000 hours using the 50% of initial light output point as the service life criterion (Narendran et al. 2000). LED failure may also be a function of temperature as indicated above.

Light Output Characteristics

Individual LEDs packaged as indicated in Figure 6-35 are directional light sources (like PAR or MR lamps) and their light is emitted as a cone. For such designs, intensity may be a more useful measure of light output than lumens. Intensities vary by color and range from 100 to 36,000 millicandelas.

Figure 6-35 – An Assembly of LEDs
The diameter of the assembly is less than 3 cm.

Efficacy

The conversion efficacy (electrical power to light) of LEDs has increased from a few lumens per watt for devices built in the 1970s to about 20 lumens per watt for white-light devices being manufactured currently. Manufacturers report that the efficacy of similar laboratory devices is now over 40 lumens per watt. Certain single-color devices (such as green) are rated higher—about 25 lumens per watt currently. Efficiency research is focused in several areas including optical geometry, materials and packaging. The optical geometry of some devices is such that a significant amount of light is absorbed by the mounting structure and package. Just as luminaires have become more efficient by minimizing optical losses using high-reflectance materials and clever optical geometry, LED packaging is utilizing low-loss coatings and careful placement and focusing of the optical components.

6.7.3 Application Guidelines

LEDs, each producing a few to 10 lumens, must usually be assembled into arrays involving dozens to hundreds of individual LEDs to provide sufficient light for their intended applications. So far, these have been primarily specialty applications such as exit signs, brake lights on automobiles, traffic signals, indicator lights and certain types of task and supplementary lighting. General lighting applications will depend on efficacy improvements and the development of white light versions that can utilize the directional characteristics, long life and ruggedness inherent in LED systems. Careful designs, however, have already yielded significant energy-saving and cost-saving results. In traffic signals, for example, an array of red LEDs can meet luminance and color requirements with just 15 watts compared to an incandescent lamp of 150 watts. An LED specification checklist will include:

- Voltage and current requirements of the array or assembly.
- Physical characteristics (size, mounting, weight, etc.) of the LED package
- Current ratings of individual LEDs (average and peak) with duty factor and pulse width included for peak data. These data indicate whether or not the LED is being overdriven.
- Light output in lumens or an intensity distribution. Intensity data are sometimes specified as minimum and maximum luminous intensity and viewing angle.
- Lumen maintenance.
- Rated life (agreed-upon service life).
- Initial color characteristics (chromaticity and color rendering—if white light).
- Color shift over time.
- Operating temperature range.

6.8 Photoluminescent Materials

While not light sources in the usual sense, photoluminescent (PL) materials may have important lighting energy implications since they can potentially replace energy-using lighting systems with passive devices that meet lighting requirements for certain applications such as luminous exit signs. PL substances are a variation of the classic "glow-in-the-dark" materials that can soak up light energy (particularly ultraviolet) and then re-emit a portion of that energy as visible light over time. Older materials used copper-activated zinc sulfide (ZnS: CU) that dimmed within hours. The new technology materials use strontium aluminate (SrAl) with rare-earth activators that can continue to emit light over days. Table 6-11 compares the luminance of the old and new materials.

Table 6-11 – Photoluminescent Material Technology

Material	**Initial Luminance (millicandelas/square meter)**
ZnS: CU	10–20
SrAl (current technology)	150–300
SrAl (next generation)	480

6.9 Resources

Below is a partial list of Web sites for suppliers of energy-efficient lamps and ballasts. Additional resources may be found as links on lighting industry Web sites such as the Lighting Research Center (http://www.lrc.rpi.edu) or Lighting.com (http://www.lighting.com).

Table 6-12 – Partial List of Suppliers of Energy-efficient Lamps and Ballasts

Company	Type of products	Web site
Advance Transformer Co.	Ballasts	http://www.advancetransformer.com
Aromat Corp.	Electronic HID ballasts	http://www.aromat.com
Bodine Company, Inc.	Emergency, inverter and electronic ballasts	http://www.bodine.com
Energy Savings, Inc.	Electronic fluorescent lamp ballasts	http://www.esavings.com
EYE Lighting International of North America, Inc.	Lamps	http://eyelighting.com
GE Lighting	Lamps and electronic ballasts	http://www.gelighting.com
Gelcore	LEDs	http://www.gelcore.com
Hatch Transformers Inc.	Electronic transformers (low voltage lighting)	http://www.hatchtransformers.com
Lumileds	LEDs	http://www.lumileds.com
MagneTek Lighting Products Group	Electronic and electromagnetic ballasts	http://www.magnetek.com/ballast
OSRAM SYLVANIA	Lamps, including LEDs, and ballasts	http://www.sylvania.com
Panasonic Lighting	Lamps including CFL types	http://www.panasonic.com/lighting
Philips Lighting	Lamps and ballasts	http://www.lighting.philips.com/nam
Robertson Worldwide	Ballasts	http://www.robertsonww.com
Ushio America Inc.	Lamps	http://www.ushio.com
Venture Lighting International	HID lamps and ballasts	http://www.venturelighting.com
Welch Allyn, Inc.	Specialty lamps	http://www.walamp.com

7. LUMINAIRES AND LIGHT DISTRIBUTION

7.1 Why Luminaires are Important

7.1.1 Light Distribution

Effective lighting design means putting light where it's wanted and needed, and eliminating light where it's not wanted or needed. Many lighting quality issues, such as task visibility, direct and reflected glare, and light pollution and trespass have to do with where light is directed and where it is minimized.

High illuminance on a desktop may help an office worker see detail in photographs or read fine print on a document, but that same high illuminance spilling into a corridor only used for foot traffic may be an energy waste. A bulletin board is more visible when it's lighted more brightly than the surrounding wall, but not if it's lighted with a track light so bright that it's distracting or uncomfortably glaring to the viewer. A brightly lit gas station canopy may appear open and attractive to customers, but if the neighbor next door has trouble sleeping because of excessive light pouring into her bedroom window, the wrong luminaire was selected.

All of these situations could have been improved by a more thoughtful selection of luminaires.

7.1.2 Luminaire Efficiency and Effectiveness

Controlling the distribution of light often reduces the efficiency of that luminaire. Lenses, louvers, reflectors and baffles all extract some efficiency from a lamp and ballast system when compared to a bare lamp. For example, a bare fluorescent striplight has an efficiency of approximately 95%, but the same lamp and ballast used in a recessed troffer with a well-shielded parabolic louver may have an efficiency of only 60–70%. Is the loss in efficiency worthwhile? In an office where video display terminals (VDTs) are used extensively, the bare striplight would produce intolerable glare, causing employee complaints and potentially lost productivity. The parabolic louver luminaire is a much better choice for this application.

A luminaire's energy effectiveness should not be judged on its efficiency alone, nor even the light source's efficacy. A 20-watt halogen MR-16 lamp is superior to a 13-watt compact fluorescent lamp in delivering illuminance on a diamond ring in a retail display, because the optics of the halogen source concentrates the light very efficiently into a narrow spot. Although its efficacy in lumens per watt is lower, fewer lamps are used to deliver the "punch" and drama necessary to attract customers to that item.

The best and most effective luminaires are those that deliver the light only where it is needed, *and* do it efficiently. Choose the luminaire with the best light distribution and higher efficiencies. (There are many variations in the photometry of luminaires, so two luminaires can be considered equivalent in efficiency if their efficiencies are within four percentage points of each other.)

In an effort to help contractors and specifiers select energy-efficient lighting equipment, the lighting industry developed the Luminaire Efficacy Rating (LER). This metric was developed to aid in the quick comparison of similar lighting products. It is calculated by dividing the total lumen output of the luminaire by the input watts, taking into consideration the ballast factor (BF) and the efficiency of the luminaire.

$$\text{LER} = \frac{\text{photometric efficiency} \times \text{total lamp lumens} \times \text{ballast factor}}{\text{luminaire input watts}}$$

Equation 7-1

Higher LERs often represent higher efficiency products. NEMA has published a set of LER values for several generic luminaire types (fluorescent "wraparound" luminaires, for example). Specifiers can check LER values for a specific product, usually published on the manufacturer's product information sheet, with the NEMA values to learn whether the product falls in the upper 25% of efficiencies for that luminaire.

The LER numbers should be used carefully, however, because LER values are based on efficiency, not light distribution. As an example, a high-precision VDT parabolic and an ordinary "building standard" parabolic fall into the same luminaire category, and the high-precision product would have a much lower LER even though it is much more appropriate for a VDT-intensive office application. Comparisons should only be made between products with similar distributions, lamping, and ballasts. For more information on this metric, see the NEMA Web site http://www.nema.org/products/div2/le5_2001.pdf.

7.1.3 Appearance and Architectural Integration

The luminaire is an integral part of the space. In addition to producing light, a luminaire's outward appearance may contribute to a space's ambiance, and thus may be an important criterion in selecting the lighting system. The lighting specifier should work with other design team members to understand whether the luminaires should be:

- Integrated into the architecture (for example, concealed behind architectural features such as beams, coves, slots, etc.; see Figure 7-1);
- Unobtrusive (for example, recessed into ceilings, walls furnishings or landscaping so that the luminaire "disappears"; see Figure 7-2);
- Visible but minimal in appearance so that they don't call attention to themselves (for example, luminaires simple in style, usually with clean geometric shapes and basic finishes, that are suspended, surface-mounted or pole-mounted; see Figure 7-3); or
- Noticeable and responsive to the style of the space (for example, the luminaire style supports the design intent of the space by mimicking finishes, contributing rhythm or scale, or suggesting a formal or casual feeling or historical period; see Figure 7-4).

Figure 7-1 – Luminaire Style: Integrated with Architecture
Photo courtesy Litecontrol. Photo by James Wilson. Lighting design: Lighting Dynamics, Phoenix, AZ.

Figure 7-2 – Luminaire Style: Unobtrusive
Photo courtesy Lighting Research Center. © 1995 Rensselaer Polytechnic Institute. Photo by Cindy Foor, Focus Studio.

Figure 7-3 – Luminaire Style:
Visible but Inconspicuous
Photo courtesy Lighting Research Center. © 1997 Rensselaer Polytechnic Institute. Photo by Steve Cridland.

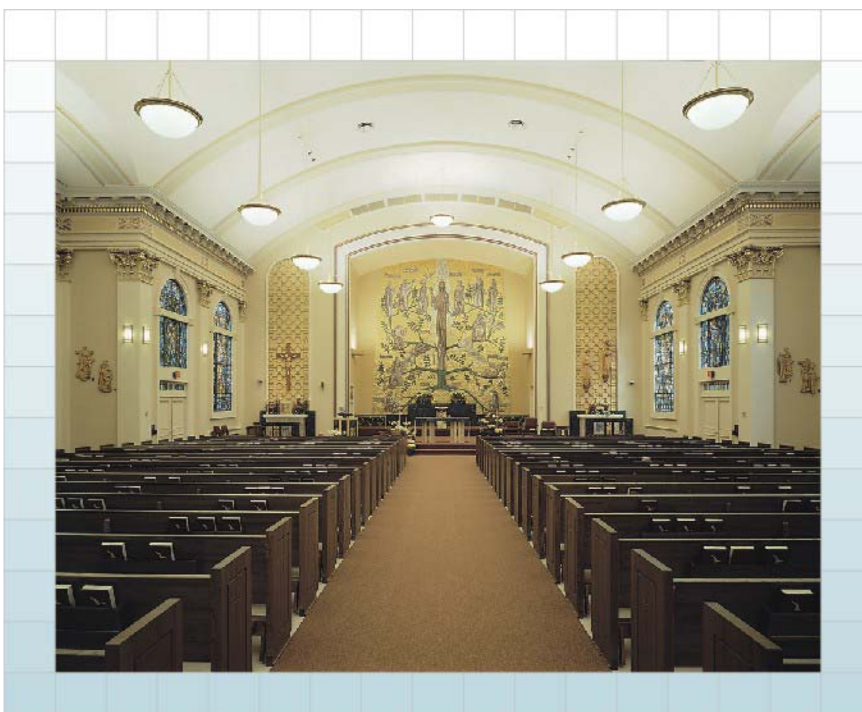


Figure 7-4 – Luminaire Style: Responsive to the Space's Style
Photo courtesy SPI Lighting Group. Architect: James G. Neu. Photography: Purcell Imaging.

7.1.4 Definition of Advanced Luminaires

Advanced luminaires may have one or more features that distinguish them from conventional luminaires:

- They may be higher in efficiency;
- They may utilize high efficiency components that reduce energy use, such as electronic ballasts or automatic controls;
- They may exhibit a better light distribution for a specific application (such as wall-washing or canopy lighting) without wasting light or producing glare;
- They may facilitate other energy efficiency strategies, such as daylighting or task-ambient design;
- They may be more durable or easier to maintain; or
- They may perform as well as conventional luminaires but with a new, compact, or different look.

Advanced luminaires often use materials new to the lighting industry or manufacturing techniques that make a product more affordable.

7.2 Electric Luminaire Components

Electric luminaires generally consist of some or all of the following parts: sources; ballasts; reflectors; shielding/diffusion components; and housings. These components are described below.

7.2.1 Sources and Ballasts

Electric light sources are lamps with their respective lamp holders or sockets. Lamps are available in a wide array of types, sizes, wattages, distributions, colors, phosphor coatings, starting and operating characteristics, styles and thermal characteristics. Effective luminaires use the most efficient light source available that exhibits the important characteristics needed to make the luminaire perform well. See chapter 6 for a thorough discussion of light sources and ballast systems.

7.2.2 Reflectors

Reflectors direct light where it is needed and may be used to shield the brightness of the lamp. Reflecting materials can be matte or specular, metallic or white, hammered or ridged, or a combination of these. It’s the job of the reflector to capture some or most of the light emitted from the lamp and redirect it to more useful zones. Each type of reflector material produces a different light distribution, as shown in Figure 7-5.

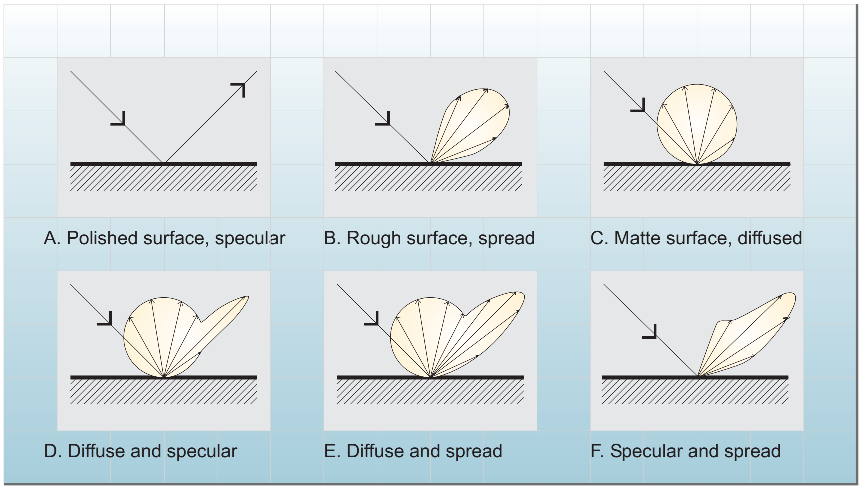


Figure 7-5 – Reflector Materials
Source: IESNA Lighting Handbook, 9th Edition

Many advanced luminaires use newly developed high-reflectance materials to improve light distribution and efficiency, and to widen luminaire spacing. These materials include:

- Anodized, specular aluminum having a total reflectivity of 85–90%
- Anodized, specular aluminum, enhanced with a multiple thin-film dielectric coating, having a total reflectivity of 88–96%
- Vacuum-deposited, specular silver, applied on the front or rear surface of a clear polyester film and adhered to a metal substrate, having a total reflectivity of 91–95%

These specular materials permit precise redirection of incident light rays, permitting precise control of light and sharper cutoffs. These differ from standard painted reflectors that produce diffuse, scattered or widespread distribution of the incident light. A disadvantage of specular materials is that when used improperly they can provide intense reflected images of the light source at certain angles, causing a “flash” of light that can create glare, be distracting or even be disorienting. Specular materials are also more susceptible to scratching, denting, or vagaries of manufacturing.

Recent advances in materials science have resulted in several higher reflectance diffuse-finish materials. These allow combining high efficiency with a uniform brightness appearance in the luminaire, and in some cases reduce the glaring appearance of the luminaire. The new diffuse reflector materials include:

- Expanded polytetrafluoroethylene (PTFE), having a total reflectivity of 98.5%
- High reflectance white-painted metal reflectors, having a total reflectivity of 90–92%

There are more high-reflectance semi-specular or semi-diffuse materials on the market with reflectances as high as 85%. Although these materials are less precise than specular materials in light control, they can significantly reduce glare and are much more forgiving to installation or maintenance abuse.

7.2.3 Shielding/Diffusion Components

Shielding/diffusion components—lenses, wave guides, diffusers, baffles, louvers, and the like (see Figure 7-6)—are used to reduce light emitted toward the user’s eyes (glare), redirect light, concentrate light, widen the light pattern, or smooth out the light pattern. These components may also serve to filter out heat or ultraviolet (UV) or radio frequencies (RF), or to provide safety protection (for example, to resist breakage and vandalism).

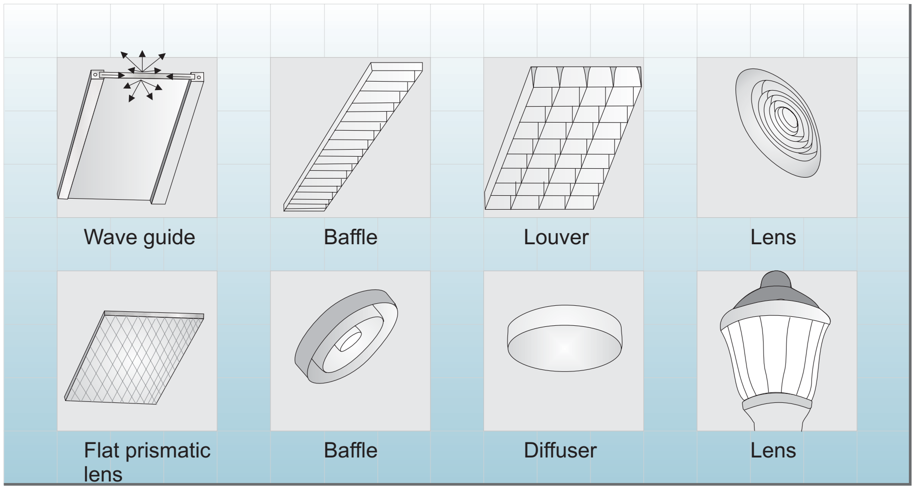


Figure 7-6 – Shielding/Diffusion Components

Refracting Materials

Prismatic lenses can be made of glass, acrylic or polycarbonate. They collect light from the light source and refract it into more useful zones, controlling glare in the process. Glass is a very durable material that remains clear over life, although it can be heavy, fragile, and more expensive than plastic materials. Acrylic remains clear over life, and is much lighter weight than glass. Acrylic cracks easily, however, and is not vandal resistant. Polycarbonate lenses are tougher, but many polycarbonates yellow and become brittle with exposure to UV radiation from daylight or metal halide lamps. There are new, high-impact acrylic materials on the market that have the clarity of acrylic with most of the toughness of polycarbonate. These are very desirable options for globes and lenses in outdoor street and parking lot lighting, industrial low-bay applications, and outdoor parking structures.

There are many different prismatic patterns that give lenses a different look and performance. Prismatic lenses should be judged on their ability to put light where needed, and on their ability to hide the brightness of the lamp behind it. The best of these, including the reverse apex lens technology, do both with high luminaire efficiency.

Wave guides are thick plastic panels designed to collect light from the material’s edge and conduct it within the material, refracting light at precise angles from the top and bottom of the material. Wave guides usually deliver most of their light upward, producing a very low brightness glow on the bottom. This is an effective direct-indirect lighting approach for VDT-intensive office spaces.

Diffusing Materials

A diffuser, which is usually acrylic or glass, differs from a lens because it does not refract light through prisms. It has a white or frosted appearance, and its job is to hide the light source and spread the light uniformly over the panel’s surface. It turns the light distribution into a soft blob, or “cosine” distribution. White diffusers are lowest in transmittance (and therefore efficiency). Newer diffusers use a sand-blasted finish or bubbles entrained within the material to produce the diffusion. Transmittances as high as 90% are available.

Shielding Materials

When larger, less-efficient light sources were the norm, there was little need to shield the view of the lamp. Now that we are using smaller sources with high lumen output (such as T-5, T-8 and compact fluorescent lamps, and HID lamps), the lamp itself is extremely bright to look at or sit under. It’s therefore more important that we shield the direct view of lamps with baffles, louvers, fins, fascias and other materials.

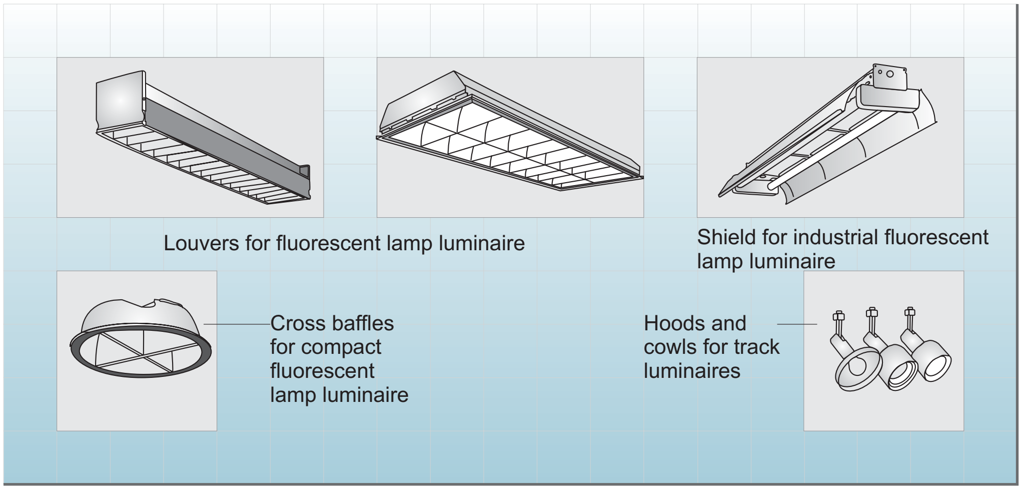


Figure 7-7 – Shielding Materials
Source: IESNA Lighting Handbook, 9th Edition

The shielding materials may be diffuse, semi-specular or specular; painted white, black or colors; have perforations; and be shaped in different ways. Figure 7-7 shows various shielding materials. If designed well, the shielding controls direct glare from the user's normal viewing angles, while allowing the luminaire to remain highly efficient. White finishes on louvers, baffles and other shielding materials maximize efficiency; black or colored finishes reduce efficiency, but may improve visual comfort.

7.2.4 Housings

Housings contain the components described above as well as electrical components, such as wiring connections, photosensors and control devices. Advanced luminaires may feature smaller, lighter, easier-to-install, or easier-to-maintain housings.

7.3 Considerations for Electric Luminaire Selection

7.3.1 General Performance Criteria

Lighting specifiers have the confusing task of choosing among the vast number of luminaires on the market. Advanced lighting design involves evaluating the luminaire's construction, ease of installation, durability and performance against the criteria listed below. (See section 4.3 for a more detailed discussion of the criteria listed below.)

- *Task visibility.* Does the luminaire provide the source/task/eye geometry that enhances task visibility? Is the task illuminance appropriate for performing the visual work?
- *Visual comfort.* Does the luminaire minimize the glare that reduces task visibility and causes discomfort?
- *Color appearance.* Does the lamp provide sufficient color contrast for the industrial task being performed? Does the lamp's spectrum support peripheral vision where needed? Does the lamp enhance skin tones where visual contact and interpersonal communication is performed? Is the lamp's color rendering ability and warmth or coolness appropriate for the type of space and its finishes?
- *Light distribution on surfaces.* What kind of light pattern does the luminaire produce, and is it harsh or soft when it hits the ceiling, wall or floor? Will the light pattern highlight important features in the space? Will the wall scallops interfere with the rhythm of artwork on the walls, or reinforce the rhythm of the artwork layout?

- *Light distribution on task plane.* What kind of light pattern does the luminaire produce on the work plane? It should be even, or people may have difficulty seeing to do their work in the darker areas.
- *Modeling faces and objects.* Does the luminaire provide appropriate light for modeling faces and objects? A concentrated downward light distribution often makes faces appear ghoulish. Faces seen in a space with uplight only may appear flat or dull. A combination of diffuse light with some downward highlighting produces the most pleasant results.
- *Flicker.* If magnetic ballasts are used, will lamp flicker produce a strobe effect or cause headaches? Clear HID lamps also produce more noticeable flicker than phosphor coated lamps.
- *Shadows.* Will the lighting create annoying shadows? Point sources are usually worse for shadowing, especially when used in concentrated downward lighting.
- *Appearance of space and luminaires.* Does the lighting system appearance support the style, rhythm and finishes of the space?
- *System flexibility and control.* Can the luminaire be switched or dimmed to save energy or reduce illuminances when needed?
- *Ease of relocation.* If tasks or furniture layouts are flexible, can the lighting system easily respond to moves?
- *Daylighting integration*. Does the electric and daylight system work effectively as a system? When the windows, skylights, and electric luminaires are well designed, electric lights can be dimmed or switched off when daylight is available, without compromising the visual environment.
- *Light trespass/light pollution*. Does the outdoor lighting design minimize light pollution or “sky glow” that may be emitted upward from decorative walkway lights, lensed cobra heads of street lights, building floodlights, or security lights? And does the design minimize light trespass (unwanted light from street lights, gas station canopies, bright signs, sports lights, security lights, or building lighting that spills onto neighboring and community properties)?

7.3.2 Photometric Data

"Photo" means light; "metric" means measurement. Photometric data describe the direction and intensity of light emitted by a luminaire (the light distribution). This information is used in lighting design and calculations. The following information appears in most photometric reports:

- A description of the luminaire, with manufacturer’s catalog number, and exact lamp type and ballast used in photometric test.
- Light intensity in candelas, expressed as a function of the specific horizontal and vertical angle from the luminaire.
- A table listing total lamp lumens and the lumen output from the luminaire in specific zones, including all light emitted downward (0 to 90 degrees), upward (90–180 degrees) and total (0–180 degrees). This table also lists the “percent of lamp lumens” for 0–180 degrees. This is the same as the luminaire efficiency, in case the efficiency isn’t listed separately.
- Spacing criterion, published for interior luminaires that direct some or all of their light downwards.
- Coefficient of utilization table, published for interior luminaires. These tables are extremely useful for quickly calculating average room illuminances by hand. (With the advance of computer lighting calculations that can perform point-by-point calculations speedily and accurately, some luminaire manufacturers are omitting the CU table in their photometric reports. Section 4.4.1 discusses these lighting calculation programs.)

Photometric tests are performed for a specific luminaire and lamp type, so the report for a parabolic louver luminaire with T-12 lamps will be different from a test for the same luminaire with T-8 lamps. The test for a 3-lamp uplight will exhibit a different light distribution and efficiency than a 2-lamp uplight. Different reflector and louver finishes will alter the luminaire's distribution, and two different manufacturer's products that look identical in the catalog may differ by over 10% in efficiency and performance.

Photometric reports are published with "relative" photometry, which means that the data are reported as though the lamps were being operated on a full light output "reference" ballast. Even though a specific ballast is named on the report, its ballast factor has been eliminated from the reported data. The candela values are reported as though the lamps were producing their rated lumen output. This means that it's very important that the designer or engineer apply a ballast factor for the ballast they are specifying to the light loss factor when doing lighting calculations, or the results could be 15% higher or lower than calculated. Furthermore, the designer or engineer must also adjust for the lumen output of the lamps they are specifying if it is higher or lower than the lamps listed in the photometric report. This is reflected in the following equation:

$$\text{Lumen ratio} = \frac{\text{Rated lumens of lamp used in application X BF of ballast used in application}}{\text{Test lamp lumens}}$$

Equation 7-2

Three of the important features of photometric reports—luminaire efficiency, luminaire intensity distribution curve, and light loss factors—are discussed below.

Luminaire Efficiency

Luminaire efficiency is the ratio of the lamp lumens that get *out* of a luminaire, relative to the lamp lumens that went *in* to the luminaire. This percentage indicates how efficient the luminaire is, but says nothing about *where* those lumens are emitted. Although high efficiency luminaires are desirable, care must be taken to avoid luminaires that ineffectively control glare or waste light by sending it where it is not wanted. As an example, a decorative street light that has an efficiency of 75%, but emits 35% of that light up into the sky where it will contribute to light pollution, is not a desirable product. A street light that is only 60% efficient, but directs those lumens downward in a desirable pattern, is usually a better product.

Similarly, while an open-strip luminaire is very efficient (up to 95%), it is ineffective mounted to ceilings in an office, where it causes uncomfortable glare for workers. A recessed luminaire with a parabolic baffle or a well-designed direct-indirect lighting system may be a better choice, even at a lower efficiency. Sections 7.5 through 7.8 provide efficiency information for specific luminaire types.

Luminaire Intensity Distribution Curve

Most interior and many exterior photometric reports are accompanied by a polar graph of the light distribution from the luminaire. At a glance these graphs give the specifier an understanding of where the luminaire is directing its light.

Imagine that the luminaire is centered at the cross-point of the x and y axes, and that you are looking at the luminaire in section (see Figure 7-8). Straight down from the luminaire is the 0 degree point (also called "nadir"), horizontal with the luminaire is the 90 degree angle, and directly above the luminaire is the 180 degree angle. These are the vertical or "elevation" angles. The graph has concentric rings radiating out from the cross-point, and each ring represents an intensity value, such as 500 candelas, 1000 candelas, and 1500 candelas.

The curve that is drawn will be above the horizontal axis for an uplight, below the horizontal axis for a downward light, and will be drawn above and below the line for a direct-indirect luminaire or a diffuse luminaire. The curve indicates the intensity of light emitted by the luminaire for a particular horizontal angle (plane).

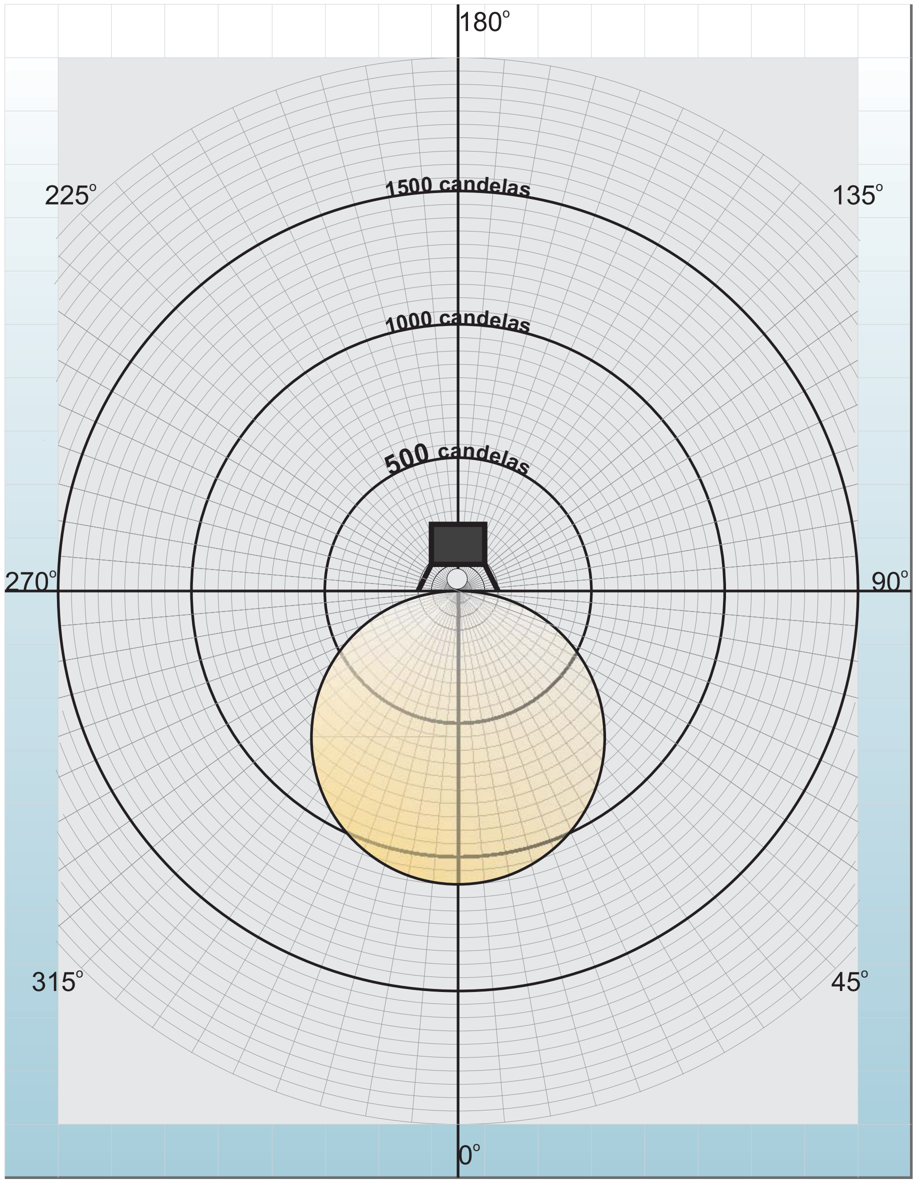


Figure 7-8 – Luminaire Intensity Distribution Curve

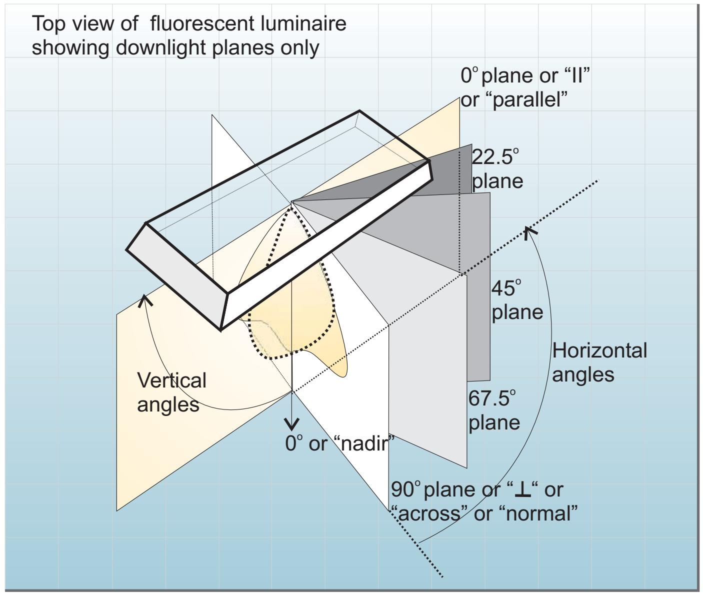


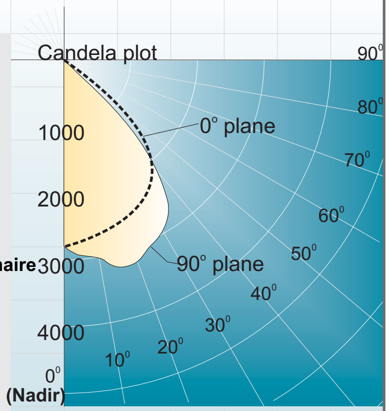
Figure 7-9 – Candlepower Distribution Curve

Figure 7-9 tells you the relative distribution of light as if you cut through the luminaire in section and looked at the light pattern created by passing a "plane" through that section. However, luminaires are not always radially symmetrical. As you look at the luminaire in plan, most linear fluorescent luminaires will emit more light perpendicular to the length of the luminaire than parallel to the luminaire. As a result, the distribution curves will be different. These are usually illustrated on a single polar graph, with the 0 degree horizontal plane marked with a solid line, and the 90 degree horizontal plane marked with a dashed or dotted line. (There may also be other horizontal planes such as a 45, 22.5, and 67.5 degree plane.) These angles as viewed in plan are also called "azimuth angles."

By listing the intensity of light at combinations of the vertical and horizontal angles, we can describe the entire three-dimensional light distribution. The numbers that correspond to the intensity curve are most often tabulated next to the curve. It is these intensity values that computer programs (described in section 4.4.1) use to calculate light levels and glare criteria.

The photometric report with candela curves for a parabolic louver luminaire is illustrated in Figure 7-10. At a 45 degree vertical angle, for example, the luminaire is emitting 820 candelas perpendicular to the length of the luminaire; you can get this from the graph if you draw an imaginary line from the cross-point to the curve along the 45 degree vertical angle, and interpolate between the rings that mark the candela values. Alternately, you can look this up in the candela table, looking at the 90 degree column and the 45 degree row. (The candela curve does not indicate that the light emitted from the luminaire stops at the edge of the curve; rather it is an indication of how strongly the luminaire emits its light in a given direction, relative to other directions. This curve, for example, indicates that the luminaire emits much light straight down, still more at 20 degrees, and much less light at 85 degree vertical angle.)

Catalog Number: Product ABC
Test 123
Lighting Company
2 x 4 recessed fluorescent troffer
(3) F32T8 lamps
27 cell semi-specular parabolic louver
2900 lumen lamps
Luminous opening: rectangular
(1.77' x 3.77' x 0.00)



Zonal Lumen Summary

Zone	Lumens	% Lamp	% Luminaire
0- 30	2463.9	28.3	44.9
0- 40	4084.5	46.9	74.5
0- 60	5436.3	62.5	99.2
60-90	46.3	0.5	0.8
0- 90	5482.6	63.0	100.0
90- 180	0.0	0.0	0.0
0- 180	5482.6	63.0	100.0

Efficiency (total)	63.0%
Efficiency (downlight)	63.0%
Efficiency (uplight)	0.0%
Total reflectance of paint	91.3%

CIE type - direct
Spacing criteria (0-Deg) 1.24
Spacing criteria (0-Deg) 1.48

Candela Distribution

	0.0	22.5	45.0	67.5	90.0
0	2866	2866	2866	2866	2866
5	2877	2877	2892	2904	2899
15	2753	2833	3002	3128	3164
25	2538	2728	2988	3087	3128
35	2200	2463	2668	2921	2984
45	1496	1670	1768	1053	820
55	178	286	274	160	94
65	28	30	35	32	27
75	7	13	11	7	7
85	0	2	0	4	2
90	0	0	0	0	0

Figure 7-10 – Typical Photometric Chart
Recessed luminaire with parabolic louver. Source: Lithonia Lighting.

The Illuminating Engineering Society of North America (IESNA) has established a protocol for putting these candela values into an electronic file so that they can be easily used in calculation software. Refer to IESNA publication LM-63 for more details. Most manufacturers offer these electronic photometric files to specifiers, available on diskette, CD-ROM, or from a Web site.

Note: Some manufacturers of floodlighting and exterior lighting products publish Type B photometry, where the 0 degree line is the primary aiming axis and the data is published in a grid rather than plotted on a polar graph. For more detailed information, see the *IESNA Lighting Handbook, 9th Edition.*

Diagrammatic photometric graphs are used throughout this chapter to illustrate the basic light distribution patterns from different luminaire types. These simple diagrams are generic, and illustrate only the primary plane of light distribution. An understanding of these patterns is very useful to the lighting designer in selecting luminaires and creating integrated lighting design strategies.

Spacing Criterion

How far apart can luminaires be spaced before the illuminance on the work plane becomes uneven? The spacing criterion, or “SC,” is listed on the photometric report to give the designer this guidance for spacing luminaires with some downward component. The spacing criterion value is multiplied by the vertical distance between the luminaire and work plane to yield the maximum spacing distance. In the case of linear or rectangular luminaires, there are two SCs, one for spacing in the direction along the length of the luminaire (called “along” or “parallel” or “||”), and one for spacing in the direction along the short side of the luminaire (called “across” or “perpendicular” or “normal” or “⊥”).

If, for example, a metal halide industrial downlight with a SC of 0.7 is hung 20 ft above the work plane, the luminaires may be spaced no more than 14 ft on center (0.7 X 20 ft) to achieve lighting uniformity on the work plane. Note that SC does not tell you whether the illuminances achieved are appropriate at that spacing. It is simply a measure of uniformity. Also note that spacing criterion was called “spacing to mounting height” or S/MH in older photometric reports. Although calculated in a slightly different way, S/MH was the same concept.

Terms for Photometric Evaluations

Coefficient of Utilization (CU) is the percentage of light generated by the lamps in a luminaire that reaches the work plane in the room. The numbers listed in a CU table may be percentages (for example, 39, meaning 39%) or may be decimal values (for example, 0.39, meaning 39%). The CU table shows the luminaire's performance under different combinations of wall and ceiling reflectance conditions and room shapes. Table 7-1 shows an example of a CU table.

The room shape is described by the **Room Cavity Ratio (RCR)** and usually ranges between 0 and 10. The RCR is a number equal to 2.5 times the wall area, divided by the floor area. Very large rooms with low ceilings will have an RCR between 0 and 1, which represents a space that uses light efficiently. Very small or narrow rooms with very tall ceilings have an RCR of 5 to 10; the large amount of wall space absorbs a great deal of light, so these rooms are less efficient at utilizing the luminaire’s lumens.

Room surface reflectances represent the percentage of light reflected from a surface, relative to the total that strikes it. Reflectances also make an enormous difference in how efficiently a room utilizes light. As a CU table shows, the CU is higher when surfaces are white (70–80% reflectance) than when they are gray or colored (30–50% reflectance). Almost all CU tables are based on a floor reflectance of 20%.

In large spaces with low ceilings and very light surfaces, a CU in excess of 100% is actually possible. Because of interreflection, a single ray of light will reach the work plane multiple times.

Table 7-1 – Sample Coefficient of Utilization Table

Coefficients of Utilization 20.0% Effective Floor Cavity Reflectance																		
P_{cc}	80				70				50			30			10			0
P_w	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10	0
RCR																		
0	.79	.79	.79	.79	.77	.77	.77	.77	.74	.74	.74	.71	.71	.71	.68	.68	.68	.67
1	.75	.73	.71	.69	.73	.71	.70	.68	.69	.67	.66	.66	.65	.64	.64	.63	.62	.61
2	.70	.66	.63	.61	.69	.65	.62	.60	.63	.61	.59	.61	.59	.57	.59	.58	.56	.55
3	.66	.61	.57	.54	.64	.60	.56	.53	.58	.55	.52	.56	.54	.51	.55	.53	.51	.49
4	.61	.55	.51	.48	.60	.55	.51	.47	.53	.50	.47	.53	.50	.47	.52	.49	.46	.45
5	.61	.55	.51	.48	.60	.55	.51	.47	.53	.50	.47	.53	.50	.47	.52	.49	.46	.40
6	.54	.47	.42	.38	.53	.46	.42	.38	.45	.41	.38	.44	.40	.38	.43	.40	.37	.36
7	.50	.43	.38	.35	.49	.42	.38	.35	.41	.37	.34	.41	.37	.34	.40	.37	.34	.33
8	.47	.40	.35	.32	.46	.39	.35	.31	.38	.34	.31	.38	.34	.31	.37	.34	.31	.30
9	.44	.37	.32	.29	.43	.36	.32	.29	.36	.31	.29	.35	.31	.29	.34	.31	.28	.27
10	.42	.34	.29	.28	.41	.34	.29	.26	.33	.29	.26	.32	.29	.26	.32	.29	.26	.25

Light Loss Factors (LLF)

Photometric test data from laboratories don't take the ballast factor into account, nor do they consider the fact that lamps emit less light as they age, or that lamps and luminaires allow less light to escape as they grow dirty over time. It's the designer's responsibility to anticipate the factors that reduce light output, and to compensate for them.

Usually this means providing higher light levels when a project is new, so that even when normal age and dirt conditions occur, the lighting system will still provide the illuminances and lighting effects needed for the users of the space. Calculation techniques (see the *IESNA Lighting Handbook, 9th Edition* for lighting calculation details) distinguish between *initial illuminance*, at installation, and t*arget illuminance*, an average value for the life of system that accounts for the light loss factors (LLF):

Initial illuminance = Target illuminance / LLF

Equation 7-3

There are two types of light loss factors that lighting designers should consider: non-recoverable and recoverable.

Non-recoverable Light Loss Factors

Non-recoverable light losses cannot be recovered by relamping or cleaning the lighting system. Most of these factors are well treated in standard references, such as the *IESNA Lighting Handbook*. Ballast factor (BF) and thermal factor (TF) are two non-recoverable light loss factors that are important for evaluating new lighting technologies. Refer to section 6.5.3 for a discussion of ballast factor. Section 7.9.3 has data that combines the thermal factor and the ballast factor into an application correction factor, which is intended for use with lighting retrofit studies.

Recoverable Light Loss Factors

Recoverable light loss factors are those factors that can be mitigated by cleaning and relamping the luminaire and cleaning the room surfaces. These factors can be calculated for a specific operating period (for example, when the installation is two years old), or for specific point in rated lamp life (typically 40%). These factors allow the designer to calculate either initial light levels (when the installation is clean and new) or maintained light levels (when the installation has aged and accumulated some dirt).

- *Lamp lumen depreciation (LLD).* LLD is the percentage of light output delivered by a lamp at a given number of hours of operation, or at a given point in its rated life. This factor accounts for the decline in light output that occurs as lamps age. LLD is discussed in detail in section 6.2.3.
- *Luminaire dirt depreciation (LDD).* Luminaire dirt depreciation from dirt accumulation on lamps, reflectors and lenses is another one of the principal recoverable light loss factors. LDD values can be as low as 0.6 for a poorly maintained luminaire. Regular cleaning increases light output from the system. Wise luminaire selection can help also because some luminaires have surfaces that attract and retain less dirt.

For example, recessed luminaires with louvers or baffles instead of horizontal lenses generally trap less dirt. Indirect luminaires collect more dirt than open direct-indirect luminaires or direct luminaires. Outdoor luminaires such as canopy lights or parking lot luminaires with horizontal lenses or cover glass often collect insects and dirt that obscures the luminaire's opening. Sealed optical systems can help keep the optical chamber clean. See the *IESNA Lighting Handbook* (chapter 9, page 9-20) for guidance in calculating LDD.

- *Room surface dirt depreciation (RSDD).* Room surfaces accumulate dirt and become less reflective with time. This can result in up to a 5–20% loss in light levels. Regular cleaning or repainting of wall and ceiling surfaces is recommended to maintain design light levels.

7.3.3 Cost Strategies

Energy-efficient lighting is often a hard sell because the initial cost of purchasing and installing the lighting equipment and controls is likely to be higher than the cost of a less-efficient system. The savings come from reduced electric utility bills and reduced maintenance costs. If the facility is owner-occupied, a life-cycle cost analysis can clearly show the benefits (that is, a quick payback) of highly efficient lighting systems. If, however, the facility is developed by one company, but the tenant pays the operating and maintenance costs, the specifier may have to specify more tried-and-true equipment that saves somewhat less energy while being very low in first cost. Life-cycle cost analysis can help the designer make these decisions. For more information on economic analysis, see section 4.4.3.

How to Calculate Light Loss Factors

The combination of ballast factor, thermal factor, dirt depreciation factors, and lamp lumen depreciation can be significant. Together they will effectively increase the number of luminaires installed. Through wise luminaire selection and precise LLF calculation, the lighting designer can avoid overdesigning the lighting system, saving energy and money for the client while providing sufficient light throughout the life of the installation. The light loss factor is traditionally calculated as follows, even though the ballast factor is an initial factor that can't be recovered through cleaning or relamping. The LLF equation is as follows:

$$LLF = BF \times TF \times LDD \times LLD \times RSDD$$

Equation 7-4

Ballast factor (BF) and thermal factor (TF) can be combined into an application correction factor (ACF), which also accounts for luminaire type and mounting conditions. Application correction factors are provided in the luminaire system performance tables in section 7.9.3.

7.3.4 Maintenance and Durability

The most beautiful, energy-efficient lighting system will soon be worthless if it can't be easily maintained. It makes no sense to mount a luminaire with short lamp life over a staircase, where relamping requires expensive scaffolding. Street lighting with a historical look will soon be replaced with more common cobra heads if the utility maintenance person can't get his or her gloved hand into the optical chamber to unscrew the burned-out lamp. And it's not a good idea to design indirect lighting in foundry offices if the atmosphere is very dirty. The specifier should select luminaires that can be easily and economically relamped, cleaned and maintained, especially when the luminaire is difficult to reach, or where atmospheric conditions are especially dirty or corrosive.

7.3.5 Manufacturing Waste and Disposal Issues

Another criterion for luminaire selection may be environmental issues related to manufacturing, packaging and disposal. What will you do in ten years with the luminaires being installed today? Is it safe to dispose of the luminaire in a landfill? Can the luminaire be torn down into its constituent parts in order to recycle the metals, plastics and glass?

Manufacturing Waste

The manufacture of luminaires often involves some hazardous materials. For example, toxic solvents are used in some paint processes, and environmental protection agencies are making it increasingly difficult for manufacturers to discharge these solvents into the waste stream and the air. Powder-coat paint systems use fewer solvents, and there is less wasted paint in the electrostatic application lines than in conventional "wet paint" lines. Anodizing of aluminum and chrome plating of metals can be toxic processes, too.

Luminaire Recycling

At this point in time it is impractical to fully recycle luminaires in North America. When disposing of luminaires, the lamps and ballasts should be removed and delivered to a company specializing in recycling these materials. Since few of the recovered materials have any value, the owner will pay a fee for this service.

Aluminum is very energy intensive to manufacture originally, but the aluminum may have some scrap value at the end of the luminaire's useful life. Steel also has scrap value and can be recycled if stripped clean of other materials. Glass can be easily recycled. Some plastic products can also be recycled.

Packaging Waste

Luminaires arrive on a job site in packaging to prevent shipping damage. Styrofoam pellets are now manufactured without chlorofluorocarbons (CFCs), and can be used many times before final disposal, but are more likely to end up in landfills than to be reused. Hot-foam protective packaging molded around the lighting component does an excellent job of protecting the component during shipping, but also creates waste. More environmentally responsible materials including cardboard packaging, shredded paper, and cornstarch-based foam pellets can be readily recycled, or will break down quickly in landfills. Some luminaire manufacturers offer packaging and shipping options to minimize waste at the jobsite. These options are often more cost effective as well.

7.4 Daylight Systems

In a daylighting scheme, the building itself becomes the luminaire. The windows and skylights deliver daylight to the interior spaces and the building surfaces act as shading devices and reflectors to shape the resultant daylight distribution. An opening in a building that admits daylight is technically called the daylight "aperture." This combination of architectural elements that deliver and shape the daylight to the space (that is, the aperture, glazing, shading devices, and primary reflecting surfaces) may be thought of as a "daylight luminaire."

Each window and skylight in a building faces a particular direction and has a view of the sun and sky that may be obstructed by the landscape or other buildings at various times during the day. An understanding of the building's architectural design is integral to the study of daylight systems.

Because the sun is always moving and daylight conditions are constantly changing, it is more difficult to develop photometric descriptions for daylighting strategies than for electric luminaires. Each building aperture type should be understood for its performance under different solar angles and sky conditions and for its net performance over the course of a typical year. Computer programs can currently model the movement of direct sun through transparent glazing, but more complex glazing systems or sky conditions often cannot be modeled well. Photometric reports for skylights under a variety of sky conditions are currently being developed, and may become available to the specifier in the near future. Such photometric reports will ultimately enable computer rendering software to provide realistic illustrations of skylight installations by time of day.

Other approaches to understanding the distribution of daylight in a space include, in order of level of detail: two-dimensional analysis with sectional drawings; physical scale models studied under artificial sun and sky conditions (or under real sky conditions); computer analysis; and/or full-scale mock-up. See section 4.4.2 for more about daylight design analysis tools.

Figure 7-11 – The Building as Daylighting Luminaire

For daylighting, the building itself is the luminaire. Here in architect Aalto's Mt. Angel Library, the architectural form of the white light "scoop" opposite the north facing clerestory windows acts as a reflector to direct diffuse daylight deep into the lower stack and reading areas. Photo courtesy Barbara Erwine.

The following subsections discuss advanced daylight systems, including system components and toplighting and sidelighting strategies.

7.4.1 Advanced Daylight Systems

Advanced daylight systems are window and skylight designs that intentionally modulate and shape the intensity and distribution of daylight in a space to meet the task requirements without glare. In most cases, daylight performs an ambient lighting function. An advanced design scheme delivers this ambient daylight uniformly across electric lighting control zones that automatically switch or dim in response to the daylight level. At other times the daylight will serve a specific task or accent function and may be designed with a distinct gradient across the space to highlight or emphasize a particular area. In either case, the goal of the advanced daylighting scheme is to create a comfortable, attractive, low glare lighting environment resulting in improved energy efficiency.

Advanced daylighting design combines multiple daylighting and electric lighting strategies to optimize the distribution of light inside the building. It considers whole building energy impacts, minimizing the building's overall energy usage and integrating the design of the daylight apertures with the electric lighting design and controls. Advanced design takes advantage of finely tuned shading strategies and high performance glazing technologies to modulate the intensity and spectral distribution of the daylight admitted to the space, minimizing heat gain during the cooling season and heat loss during the heating season. The size of apertures and their glazing and shading design change for each orientation to reflect the expected solar angles, heat gain and glare criteria. These new glazing and shading options are detailed in section 7.4.2 below.

The direct sun and even the bright sky are very intense light sources. Direct sun can range up to 160,000,000 candelas/ft² and a cloudy sky can average 200 candelas/ft². Both of these can produce glare when viewed by an occupant in an interior space with less luminous surfaces. Control and diffusion of this bright source is a key challenge of daylighting design (see Table 6-1).

One of the strategies used in many advanced designs is to differentiate a window's view and daylighting functions. A *view window* should be transparent, located at eye level, directed toward the view of interest and minimize glare. It may have lower transmission glazing and/or a manual shading device to reduce glare. In addition, illuminating the adjacent wall surfaces with additional daylight from another direction, or from above, is an important strategy to reduce contrast glare potentially created by a view window.

A *daylight window* designed to provide even illumination across the space should be high in the wall or ceiling (to bring daylight deeper into the space), be spaced uniformly around the area, and have relatively high visible light transmission. It may have baffles or diffusers to redirect or shade the direct sunlight and prevent glare. Because of these different design requirements, advanced designs may provide different apertures for each of these functions, or may divide a window into a daylight component above and a view component below. Another approach to this differentiation is to let a grid of skylights provide the ambient daylight in the space and judiciously space view windows at eye level in the exterior wall.

7.4.2 Daylight System Components

A daylight system is composed of the light source directly or indirectly from sun or sky, the daylight aperture with its filters, reflectors and shading elements, and the primary interior reflecting surfaces. This section investigates these various components and their function in delivering and shaping daylight distribution in the space.

Sun as Light Source

Sources of daylight include the sun, which provides intensely bright beam radiation; the blue sky, which provides about one-tenth the sun's illumination as a diffuse source; and clouds, which can function as a light source with characteristics anywhere between the two. As described in section 6.3, daylight is a dynamic source, constantly changing all of its performance characteristics (intensity, color, direction, focus and efficacy). Some of these characteristics change with absolute predictability (sun position, for example); some change with approximate predictability (seasonal weather patterns); and some change with no predictability at all (hourly weather-driven changes throughout a day). To simplify the problem, it is often useful to consider a limited set of daylight conditions that describe the range of conditions encountered. For example, blue sky, bright cloudy sky, low angle sun and full direct sun define four very different conditions that can be studied.

Daylight Openings (Aperture)

Daylight openings, or apertures, have a particular size and orientation and may be located on a building's roof (toplighting) or walls (sidelighting). Their resulting exposure to the sun and sky is modulated by the sun's movement, weather patterns and site obstructions (like exterior buildings, landscape and topographic features). Early choices about building massing and orientation may limit options for aperture placement and size, and in turn, critically affect daylight distribution, glare and building energy loads. Although selection and design of shading devices, reflectors and glazing materials can mitigate these impacts, it is easiest to design the apertures correctly in the first place.

Advanced schemes consider the daylighting strategy early in schematic design to generate a building form with apertures that respond to the building program and site conditions to deliver the desired daylight with minimal energy use. Guidelines for optimum aperture locations and size are discussed in the sections on Toplighting (section 7.4.3) and Sidelighting (section 7.4.4) below.

Directing the Daylight: Reflectors and Refractors

Some advanced daylight systems utilize specular, semi-specular or diffuse reflectors and refractors to redirect sunlight into the building's interior or to reject intense direct sun during the building's cooling-dominated time. These materials may be in the plane of the glazing (sometimes incorporated into the glazing itself) or on the exterior or interior of the aperture.

The reflection or refraction may be accomplished with diffusing reflective surfaces, specular or semi-specular reflecting metal surfaces or coatings, prismatic glass or plastics, holographic films or a Fresnel lens.

Current advanced products include:

- Mirrored, prismatic or holographic surfaces above a skylight or outside a window. These are designed to equalize the direct sun contribution in the space over time by redirecting low angle early morning/evening and winter solar angles into the space and shading high angle midday summer angles. This increases the direct sun contribution when it is weakest and reduces it when it is the strongest, thus minimizing unnecessary heat gains (at summer midday) and extending the hours of useful daylight (in early morning, evening and winter).

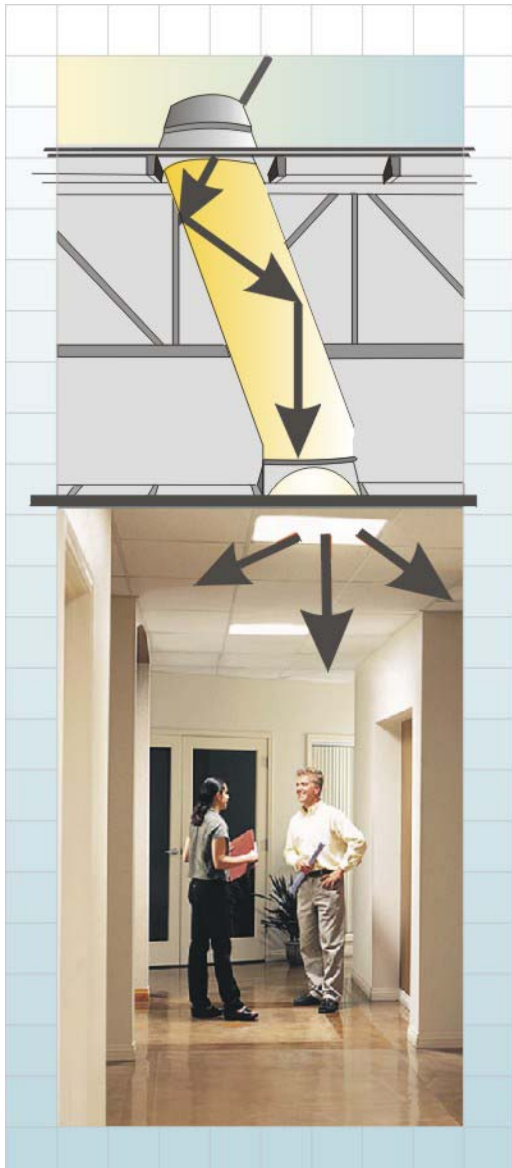


Figure 7-12 – Skylight System with Clear Dome, Reflective Shaft and Bottom Diffuser
High angle sunlight passes directly through the clear dome and reflects off mirrored shaft in the ceiling plenum before being introduced into space below through a drop-in diffuser panel at the ceiling plane. Additional low angle winter sunlight is captured by a curved reflector on north side of the dome. Photo courtesy Solatube.

- Exterior “collector” devices that may be mirrored, prismatic, Fresnel lens or selective surfaces that collect and redirect direct sun into a light guiding system.
- Mirrored or prismatic surfaces that reflect or refract direct sun through a hollow (“light pipe”) or solid (“fiber”) light guide system to deliver it deeper into the space (see Specialty Lighting Products in section 7.7).
- Reflective (specular, semi-specular or diffusing) or refractive horizontal lightshelves and louvers that redirect sunlight onto the ceiling plane so that it’s available deeper in the space.

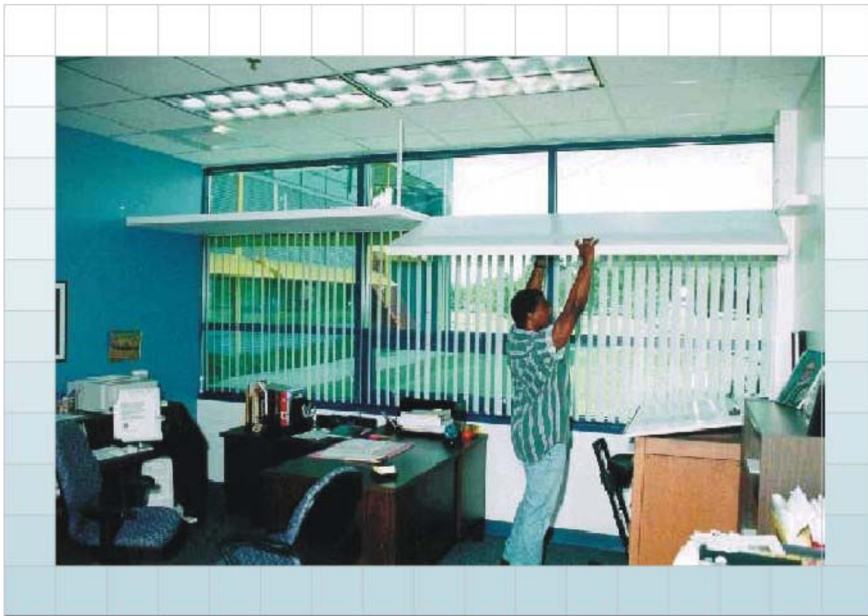


Figure 7-13 – Reflective Lightshelves

Worker installing a commercially available lightshelf product to reflect daylight onto the ceiling of the office area, allowing daylight to penetrate deeper in the space. Vertical blinds below the lightshelf reduce glare for the view glazing. Photo courtesy The C/S Group.

- Reflective or refractive materials in the plane of the glazing that redirect sun to the ceiling of the space.
- Interior louvers under a skylight or clerestory that prevent direct sun penetration, redirect daylight onto the ceiling or walls, and reduce glare by limiting views of the bright glazing. These louvers may be fixed or operable (to adjust the daylight level transmitted through the toplighting system).

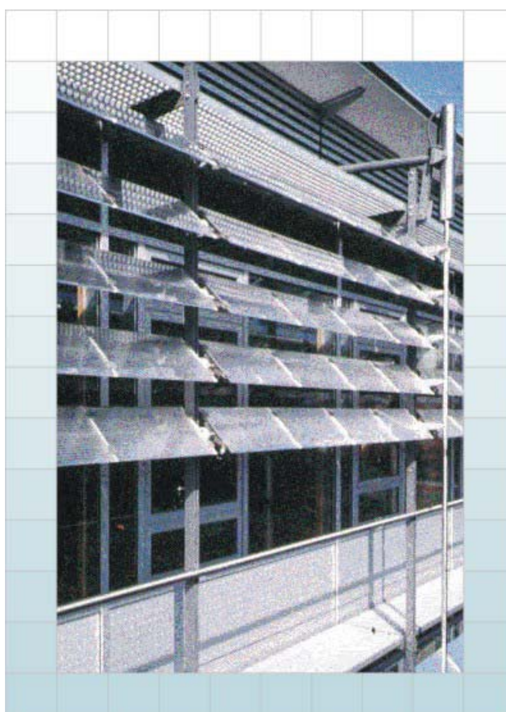


Figure 7-14 – Prismatic Louvers

Prismatic louvers outside these south-facing windows shade lower glazing and redirect sunlight onto the ceiling of the space. Photo courtesy Bomin.

Be careful to avoid glare when designing reflective systems. This is especially critical when direct sun is being reflected or refracted in the space. Reflectors below eye level will cause glare for the occupants. The surface of a reflective or refractive system can be very bright even if most of the light is being redirected to the ceiling. Direct sun that is reflected outside a building may also cause disabling glare for other buildings' occupants or pedestrians and auto traffic at specific angles. Some locales have restricted use of reflective glass in sensitive situations. Specular reflectors that redirect sunlight to the ceiling or an interior wall can create strong patterns of light that may appear overly busy or glaring. See section 4.3.2 for more about avoiding glare.

Shading: Opaque Shielding Components

In a daylight system, opaque shielding devices serve three functions: to shade glazing from excessive solar gain; to enhance views by reducing the contrast between the interior and exterior light levels; and to reduce glare from direct view of the sun or sky.

The direct sun can deliver over 300 Btu/h-ft², easily overheating interior spaces with unshaded windows. The attendant air conditioning loads can eclipse any energy savings from an electric lighting control system.

Exterior views may be illuminated with 9000 fc of daylight while interior spaces have only 50 fc. Exterior overhangs, louvers, lightshelves and fins can reduce daylight levels adjacent to the window and modulate the contrast between the exterior and interior. To minimize glare, bright glazing surfaces can be shielded from view by lightshelves, louvers, or baffles.

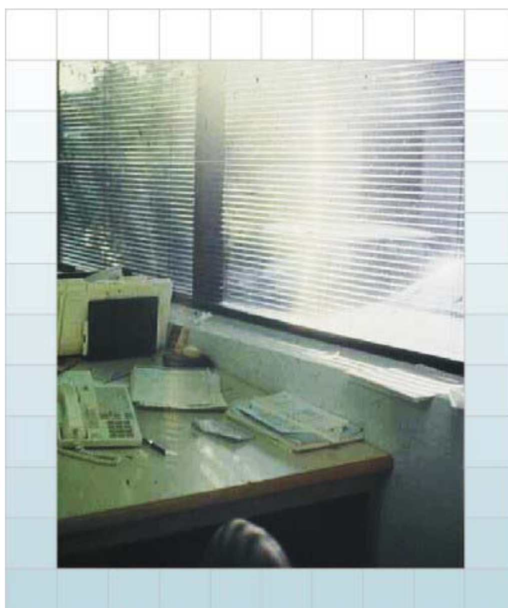


Figure 7-15 – Window Glare
Photo courtesy Lisa Heschong

In daylighting, these shielding components are sometimes an integral part of the building architecture (for example, when the view of a skylight is obstructed by the skylight well that connects the ceiling and roof plane) or they may be added as a separate device to the building (for example, interior blinds).

Housings

The glazing spacers, window frames and mullions affect the energy performance of windows by impacting the overall window U-factor and infiltration rates. They also affect comfort and maintenance by controlling leakage, condensation, and structural strength and, in some cases, by allowing natural ventilation. Recent advances in warm edge spacers put a thermal-break butyl sealant between the steel spacer and the glazing. This reduces conduction at the edge of the glazing, resulting in a lower U factor for the total window performance. National Fenestration Rating Council (NFRC) window ratings will show this total window U-factor and in the future will also show ratings for infiltration and condensation.

Glazing Options: Transparent/Translucent Filtering Components

Although not all electric luminaires incorporate a transparent or translucent filtering component, all daylight apertures will have a transparent or translucent glazing layer between the solar source and the interior space. This layer may consist of a single pane of glass or plastic or may involve multiple layers of glass, plastic and films separated by air spaces. The glazing layer serves as a weather barrier and acts to filter the incoming daylight.

Originally most glazing layers were designed to be as transparent and spectrally neutral as possible to let in the maximum daylight. But today a wide range of glazing products can be optimized to selectively absorb, reflect or transmit different portions of the solar spectrum. High-performance glazing techniques, including double glazing, reflective and low-emissivity coatings, and tinting, have become an important aspect of daylighting design and energy conservation in modern construction.

Glazing Specifications

The National Fenestration Rating Council (NFRC) has established a rating system for glazing assemblies (glazing, frame and spacer). This system rates and labels each window assembly for the following specifications, as a whole unit. (NFRC also plans to add ratings for condensation and infiltration by the end of 2001.) Refer to Table 7-2 for representative glazing specifications for single, double and triple glazing.

U-factor (or R value, U = 1/R) measures the heat transfer of a window assembly. The lower the U-factor (or higher the R value), the lower the rate of heat loss and of heating energy consumption. U-factors may be specified as “center of glass” (COG) or whole window (preferable). NFRC is now labeling windows with a whole window value. Because the U-factor degrades at the edge of the assembly, the COG value will be lower (better) than the whole assembly value. Single-pane windows typically show a center of glass U-factor in the range of 1.0 to 1.2 Btu/hr-ft^2-ºF; double-pane windows start at about .48 for uncoated glazing and may be lowered to .29 with the use of specialized low-e coatings and gas fill.

Solar Heat Gain Coefficient (SHGC) measures the fraction of solar heat gain transmitted through a window. Daylighting designers seek to maximize useful visible daylight while minimizing solar heat gains that, if unchecked, can cause cooling energy costs to outweigh the energy saving benefits of daylighting. (SHGC replaces the Shading Coefficient, SC, which measured heat gain relative to a 1/8 in. thick, clear, double-strength glass. SC = 1.15 * SHGC.)

Visible Light Transmittance (VLT) refers to the fraction of light within the visible spectrum that is transmitted through the glazing. For maximum daylighting, this value should be as high as possible, assuming that glare is controlled. Clear single-pane glass has a VLT of 0.88; reflective or very darkly tinted glass may have a VLT of 0.1 or less.

Table 7-2 – Representative Glazing Specifications

This table shows representative trends in glazing performance for a variety of glazing configurations. U-factors are shown for center of glass (COG); whole window values will be higher. Choose a glazing with high performance index to efficiently daylight air-conditioned buildings. Commercial products may vary from these values depending on tint and coating specifications; check manufacturer's literature for specific data.

	Tint/Coating	Gas Fill	COG U-Factor	Visible Trans. (VLT)	SHGC	Performance Index Visible/SHGC
Single glazing	Clear	NA	1.1	0.88	0.82	1.1
Double glazing	Clear/clear	Air	0.48	0.78	0.7	1.1
	Std. low-e/clear	Air	0.33–0.35	0.75	0.6 - 0.7	1.3 –1.1
	Std. low-e/clear	Argon	0.3	0.75	0.6 - 0.7	1.3–1.1
	Gray/clear	Air	0.48	0.39	0.45	0.87
	Gray reflective/clear	Air	0.48	0.17	0.33	0.51
	SS blue-green/clear	Air	0.48	0.63	0.4	1.58
	SS low-e/clear	Air	0.29	0.7	0.37	1.9
	SS green/SS low-e	Air	0.29	0.56	0.27	2.1
Triple glazing	Clear/clear/clear	Air	0.32	0.75	0.7	1.1
	Clear/low-e/low-e	Argon	0.17	0.64	0.56	1.14

Notes:
COG = Center of Glass SHGC = Solar Heat Gain Coefficient SS = Spectrally Selective VLT = Visible Light Transmittance

An advanced glazing assembly is optimized to respond to the building's energy needs and to deliver appropriate levels of daylight to the space. The goals of these advanced products may be divided into two general categories, "warm" glazing that reduces heat loss, and "cool" glazing that reduces overall solar heat gain:

"Warm" Glazing (reduces heat loss)

Since opaque portions of a building envelope can easily achieve much lower U-factors than glazed areas, the building fenestration represents a significant heat leak in the envelope. Buildings that have high heating loads, such as residential buildings or small commercial buildings in colder climates, can benefit greatly from glazing materials that minimize U-factors and reduce heat loss.

Advanced products for these buildings incorporate multiple layers of glass or plastic and one or more low-e coatings (or films) separated by a cavity filled with an inert gas (argon or krypton). The low-e coatings reduce the emission (radiation) of heat from the pane of glass. Most low-e coatings are relatively soft and must be located on the second or third surface of double glazing or suspended in a film between the glazing layers so that they are protected from abrasion. For interior heat retention, the low-e coating should be on the #3 surface (see Figure 7-16). However, design professionals don't always have a choice on the surface placement of the coating. Some manufacturers always locate the low-e coating on surface #2 to minimize heat buildup in the glazing cavity and reduce the risk of potential seal failures. This will have only a minor impact on the unit's energy performance.

Other advances in warm glazings are low-conductivity frames and warm edge-spacer technology. Glazing systems that optimize all of these features may achieve a "center of glass" U-factor as low as 0.1.

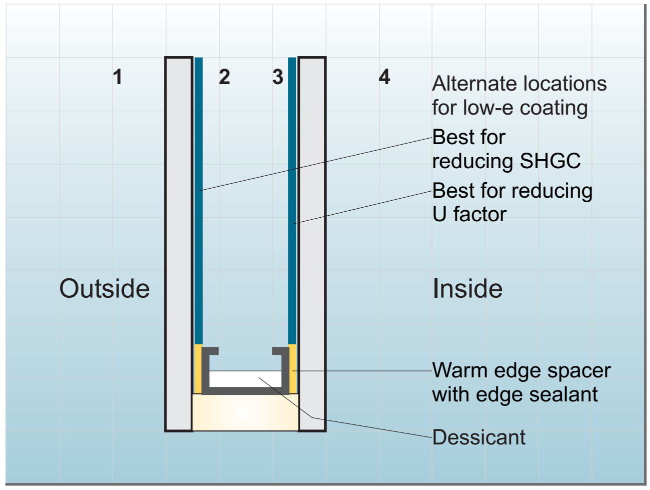


Figure 7-16 – Surface Numbers for Glazing System

Surface numbers for glazing system in a double glazed window, showing common locations for low-e coatings. Warm edge spacer reduces heat loss, lowering the overall window U-factor and minimizing condensation problems.

"Cool" Glazing (reduces overall solar heat gain)

These products reduce cooling loads on buildings by absorbing or reflecting solar radiation. Most large commercial buildings have substantial cooling loads for much of the year, and thus benefit from cooling load reductions. Cool glazing products may decrease transmission uniformly across the solar spectrum or may selectively transmit one portion of the spectrum while absorbing or reflecting another. Advanced "cool" glazing products selectively transmit visible light while decreasing the UV and IR heat. The performance index, which describes the glazing material's efficacy, is defined as the ratio of visible light transmission to solar heat gain (VLT/SHGC). The higher the performance index, the better the glazing material is at enhancing daylight while reducing solar gains. Glazing materials with a high performance index (ratio greater than 1.3) are called selective glazing materials because they selectively transmit visible radiation while blocking ultraviolet and infrared frequencies.

Glazing products that reduce solar gains include:

- "*Selective" Low-e Coatings.* The greatest glazing advances in recent years have been in the area of spectrally selective low-e coatings. These coatings selectively transmit visible light and reflect IR and UV. In addition to providing low U-factors, these second generation low-e products reduce solar gain through the window with minimal visible color. They are excellent choices for unshaded windows that are exposed to solar gain during the cooling season. These selective low-e coatings are characterized by high VLT and low SHGC with a ratio of VLT to SGHC of greater than 1.5. For solar heat gain reduction, these selective low-e coatings should ideally be on the #2 surface (see Figure 7-16).
- *"Tinted" Glazing* (tints, gels, etc). Aside from its artistic uses (for example, stained glass), tinted glazing may be used to complement an architectural color palette and/or to decrease solar gain and glare. Tinting is usually achieved by the addition of a rouge to the silicon when the glass is manufactured. It may also be created with a colored gel laminated to clear glass or suspended within the glazing layers. Tints reduce a glazing's overall transmission, and different tint colors have variations in transmission levels across the solar spectrum. Green and blue-green tints will selectively transmit more visible light than solar heat (UV and IR), but most gray and bronze tints will have the opposite effect. The energy performance of a tinted glazing can be evaluated from its performance index, the ratio of visible light to heat that it transmits (tinting has very little, if any, effect on U-factor). For more information, see the sidebar Performance Characteristics of Tinted Glazing.

- *Reflective Coatings*. Reflective glazings are created by depositing a metallic coating on a transparent substrate producing a mirrorlike appearance. Most of these products reflect more visible light than UV or IR, so they reduce glazing efficacy. Thus, they are not good choices for energy efficient design.
- *Frits and Screens.* These products decrease solar gain by covering the glazing with an opaque patterned filter. A frit is a ceramic paint fired on the surface of the glass in a pattern during the manufacturing process. Screens may be suspended within the glazing layers, applied to the surface of the glazing with an adhesive, or laminated to the glazing.

These products reduce transmission equally across the whole solar spectrum, so they aren't selective and don't increase glazing efficacy. Since these products imply the use of a larger glazing area than is needed to meet the lighting needs, they pose an energy penalty for heat loss and U-factor (see above under "Warm" Glazing). Ideally, an advanced design sizes the daylight glazing area to meet the desired light levels and controls glare by restricting direct view of the glazing material, making frits and screens unnecessary. However, larger glazing areas may be desired to provide view or support an architectural objective. In these cases the use of a frit or screen will allow larger glazed areas while reducing solar gains.

Some advanced new glazing products laminate photovoltaic cells in a screen pattern that allows the transmission of daylight between the cells. These building-integrated photovoltaic (BIPV) approaches provide filtered daylight while generating energy and may justify much larger, energy-efficient glazing areas for atria and south-facing surfaces.

Dark frits and screen patterns have the advantage of visually "disappearing" to permit better views of the exterior but have the disadvantage of absorbing heat. Light-colored patterns restrict views more but are better at reflecting both heat and light and read better as an interior "surface" when illuminated at night.

Performance Characteristics of Tinted Glazing

Bronze and gray tints reduce glazing efficacy, while blue/green tints increase efficacy. Because the photometric response of the eye peaks at about 555 nm (the blue/green portion of the spectrum), green glazing products have the highest VLT for the lowest SHGC. These products are naturally energy efficient and are frequently referred to as "high performance" tints. They will have a VLT/SHGC ratio of 1.3 or greater.

Table 7-2 lists common glazing tints and their respective VLT and SHGC.

Tints also change the color temperature and CRI of the transmitted daylight, but there are no specifications for either the CCT or CRI of daylight transmitted through a tinted glazing. Gray tints have a color-neutral appearance and will have the least impact on color temperature and CRI.

Tints may distort both the color of objects viewed through the glazing and the color of objects illuminated by daylight that has been transmitted through the glazing. These effects must be evaluated by visually inspecting the glazing in an appropriate setting. Because of the eye's color adaptation, people in a space with tinted glazing won't perceive that they are in a colored environment (the eye sees the dominant light source as white). However, the glazing color will be perceived if it is viewed adjacent to clear glass.

Active and "switchable" tints that darken in response to the daylight level or an electric stimulus are under development and have established niches in small glazing applications like sunglasses and automotive mirrors. As this technology develops and costs decrease, large-scale versions of these products will provide buildings with "variable apertures" that deliver light based on current building needs.

- *"Diffusing" Glazing*. Diffusing glazing materials are commonly used for toplighting strategies. Glazing diffusion may be accomplished by white pigments, imbedded fibers (fiberglass) or surface treatments like frits or sandblasting, all of which reduce visible light transmission as the diffusion properties increase. Glass and plastic products with prismatic surfaces, on the other hand, can maintain high visible light transmission with high diffusion performance. Diffusing glazing products are usually evaluated by a rough visual inspection (high diffusion materials will not allow any image to be seen through the material) or by observation of the uniformity of diffused sunlight and the lack of "hot spots" on the floor of the space. Photometric descriptions of diffusing glazing materials performance may become commercially available in the near future.

Although diffusing glazings spread the intensity of the direct sun more evenly in the space, direct view of the bright diffusing surface is a source of glare and may be especially disturbing because it provides no informational view. Keep diffusing glazings out of the normal field of view.

Switchable diffusing glazing changes from clear to diffuse in response to an electrical or thermal signal. It has been used for interior applications (conference rooms, for example) but has had limited use in exterior windows because of its high cost and instabilities from exterior thermal and UV stresses. As these products improve, they promise to increase the energy and lighting performance of apertures (especially skylights) by automatically responding to changing sky conditions.

- *Retrofit Films.* Retrofit films are available to serve most of the functions noted above, including low-e, tinted and reflective films, screens, and special diffusion or refraction properties. They are often a good solution to improve glazing performance on an existing building without replacing the windows. However, an applied film can add thermal stresses to a glazing assembly that the assembly was not designed to carry (including increased risk of seal failure and glazing cracks). Note that most window manufacturers void the warranty for any window that has been retrofitted with a film.

Glazing Performance and Maintenance:

Glazing should be cleaned on a regular schedule to maintain the investment in the daylighting system. The accumulation of dirt on glazing surfaces reduces the visible light transmission in addition to degrading the appearance of the glazing and views. This decrease in visible light transmission compromises the daylighting performance, reducing light levels and potential energy savings.

When calculating the expected interior daylight levels, the designer should estimate a "dirt on glass" factor to describe the expected reduction in visible light transmission from the accumulation of dirt on the exterior glazing surface. The factor depends on the glazing cleaning schedule, the slope of the glazing (horizontal glazing accumulates more dirt than vertical), the cleanliness of the exterior environment, and the availability of rain to effect a natural cleaning. Dirt on glass factors may range from .5 for horizontal glazing cleaned infrequently in a dirty industrial environment to .9 for vertical glazing cleaned every 6 months in a relatively clean urban environment.

7.4.3 Toplighting Daylight Systems

Design Considerations

Toplighting refers to placing daylight luminaires in the ceiling/roof plane of the building. An advantage to toplighting schemes is that they can locate daylight apertures directly over task areas, distributing daylight uniformly. They can also reduce the potential for glare by keeping the source of daylight out of the direct line of sight. Toplighting, of course, can only easily be provided for one-story buildings or for the top floor of multistory buildings. However, as discussed in section 3.2.1, this represents at least 60% of existing commercial floor space, making it an important energy efficiency strategy. Skylights and monitors with enclosed, reflective wells can conduct daylight to lower floors. But since this is expensive and space consuming, it is used infrequently and won't be considered further here.

Glare Control for Toplighting

Advanced toplighting schemes minimize glare by preventing a direct view of the glazing. This can be accomplished by using baffles, structural elements, or skylight well geometry that provides a sufficient visual cutoff angle. Locating the overhead daylight source in a very high ceiling can also reduce glare by keeping it out of the direct view of occupants. Glare from overhead daylight sources is also reduced by controlling the contrast ratios between the light well surfaces and the ceiling. Diffusing the daylight across large well or wall surfaces, and brightening the ceiling with reflected daylight from the floor both work to reduce these contrast ratios.

Figure 7-17 – Toplighting in Elementary School Classroom
This classroom has east-facing sawtooth monitors with white painted baffles at the ceiling plane to diffuse direct sun. Photos courtesy Barbara Erwine.

Integration of Electric Lighting with Toplighting

Toplighting apertures may contain electric luminaires to provide nighttime lighting. These should not restrict the flow of daylight from the aperture, but may pleasantly light the aperture at night while delivering usable light to the interior. Alternatively, the upper aperture volume does not need to be directly lit at night, lowering the apparent ceiling height. They should be switched or dimmed in response to the available daylight. Adjustable louvers or shades inside the skylight well or monitor may be used to manually or automatically adjust daylight levels or to darken the space for audiovisual (AV) use.

Toplighting Options

Unless they incorporate a reflector beneath them that redirects daylight to the ceiling, most toplighting schemes provide direct downlighting in the spaces they serve. Their daylight distribution depends on the type and orientation of the glazing and design of their surrounding reflective surfaces (and of course on the relative position of the sun and the sky condition).

Skylights

Skylights have a horizontal (or substantially horizontal) aperture to the sky. The glazing that covers this opening may be flat, domed, faceted, gabled, or pyramid shaped.

Solar Gain. The horizontal orientation makes a skylight more available to high summer midday solar gain than to lower angle winter or morning/evening sun angles. This summer increase of solar gain is a disadvantage for cooling-dominated buildings and does nothing to offset the seasonal disparity in daylight illumination. However, it is a benefit in predominantly overcast sky conditions (where sky luminance is three times brighter at the zenith than at the horizon) and in dense urban or heavily forested sites (where the predominant sky exposure is from above). The most advanced skylight designs increase low angle sun penetration, while reducing high angle sun penetration. This may be achieved with skylight geometry, special lenses, reflectors, or roof monitor or skylight well geometry.

Flat vs. Sloped Roofs. Most commercial and industrial skylights are installed on flat roofs, where the skylight can "see" almost the full hemisphere of the sky. A skylight on a sloped roof, however, will have only a partial view of the sky. There may be times of the year or day when direct sun cannot even reach a sloped skylight. For example, a sloped east-facing skylight may receive direct sun in the morning but no direct sun—only diffuse sky light—in the afternoon. Thus it will provide a modulation in light levels from morning to afternoon, yielding more morning light and less afternoon light than a comparable skylight on a flat roof.

Skylight Shape. The shape of the skylight glazing can also impact the amount of light it provides at high and low sun angles. Glazing surfaces transmit the most light at incident angles normal to the glazing surface. As the angle of incidence is reduced, more light is reflected; this is especially severe at very low angles. Domed (bubble), pyramid, faceted and Fresnel-lensed skylight glazing can intercept substantially more sunlight at the critical low angles and increase the illumination delivered below by 5–10% in low angle morning and evening hours of the day.

Clear vs. Diffuse Glazing. Although clear skylights may be used to provide direct sun patches and lively accents for transient spaces, for ambient working light in a commercial space, the direct sun component must be diffused with either diffusing glazing or a series of baffles or louvers under the skylight.

Skylight Well. The skylight well brings the daylight through the roof and ceiling structure and simultaneously provides a means for controlling the incoming daylight before it enters the main space. The design of the skylight well shapes its daylight distribution and may include baffles or louvers to control glare and modulate the light levels. Deep, narrow wells trap much of the daylight and deliver a relatively narrow distribution of down light to the space below (see Figure 7-18A). This may be advantageous for VDT screen applications that have low glare tolerance. Wide, splayed, shallow light wells disperse light more evenly over a broader area and allow skylights to be spaced farther apart (Figure 7-18B). A deep narrow well can be designed to distribute light more broadly if the well has specularly reflective walls and a diffuser at the bottom (Figure 7-18C). Care should be taken to make sure that any diffuser does not create glare problems by being overly bright or in the occupants' direct line of sight.

Light-colored well walls reflect more light downward into the space and create a gradual brightness transition between the bright glazing surface and the darker ceiling. Dark well walls should be avoided because they absorb the light and increase contrast and glare.

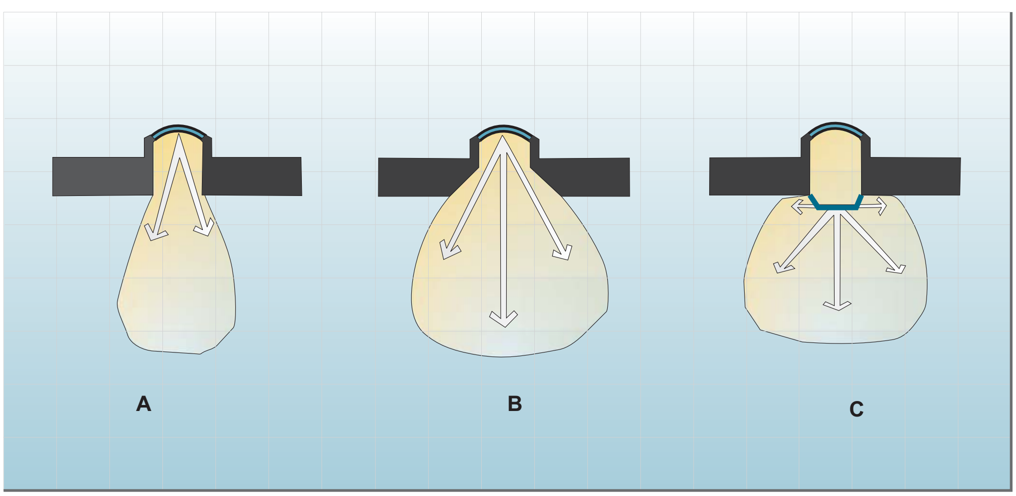


Figure 7-18 – Light Well Shapes and Daylight Distribution
Light well shapes and daylight distribution for skylights with a straight, narrow light well (A); a splayed light well (B); and a mirrored reflective light well with a bottom diffuser (C).

Skylight Size and Spacing. Skylights save energy by reducing electric lighting usage, but increase building energy loads with solar gains during the cooling season and heat losses during the heating season. The appropriate skylight size depends on the building type, location (climate), energy loads and desired light levels. Assuming that the electric lights are on automatic photocontrols, skylights with high visible light transmission (greater than 50%) should typically be distributed uniformly across the space and have a total glazed area equal to about 3–9% of the floor area to provide adequate daylight levels while minimizing overall building energy use. For even distribution of daylight, skylights are usually spaced about 1.5 times the floor to ceiling height. Simple computer tools can help determine the optimum size for a given building type, climate and skylight specification. One such tool, "SkyCalc," is available for many U.S. climates and is available free on the Web (http://www.energydesignresources.com). See section 4.4.2 for a discussion of daylighting design analysis tools.

Clerestories, Monitors and Sawtooth Monitors

All three of these toplighting schemes—clerestories, monitors and sawtooth monitors —are characterized by vertical (or nearly vertical) glazing that projects up from the roof plane to admit daylight to the space. Their orientation, glazing and structural form affect their efficiency and distribution of daylight in the space.

- A clerestory window is high vertical glazing in an exterior wall or a vertical wall projecting up from the roof (see Figure 7-19A). When it is part of an exterior wall, it's a form of high sidelighting, which is discussed in section 7.4.4.
- Monitors pop up from the roof plane to provide vertical glazing on one or (frequently) two sides (Figure 7-19B).
- Sawtooth monitors have a sloped roof section connecting the vertical glazing and the roof deck and may occur singly or as a series of roof forms (Figure 7-19C).

These toplighting schemes use daylight from the direct sun and diffuse sky and also sunlight reflected from the roof and adjacent monitors. A highly reflective roof can add significantly to the amount of daylight gathered. North- and south-facing glazing orientations are easiest to design because they avoid the low east/west solar angles and the modulation of daylight from morning to afternoon. Typically, north-facing apertures employ clear glazing. South-facing apertures use either translucent glazing or baffles to diffuse the direct sun. For north-facing monitors, the combination of diffuse north sky light and twice-reflected sunlight (reflected from roof and then the monitor interior) yields approximately half the illumination as does a translucent horizontal skylight (Moore 1985, 95). A comparable south-facing monitor with translucent glazing gives illumination about equal to the skylight, but with an asymmetric distribution that peaks slightly north of the opening.

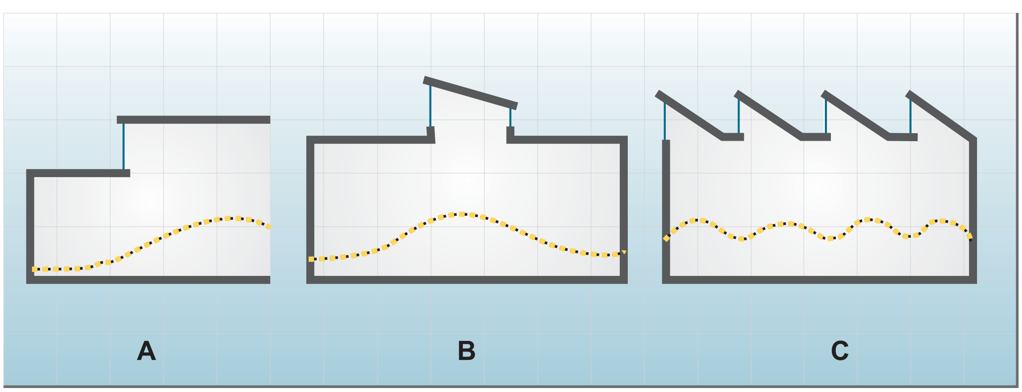


Figure 7-19 – Light Distributions: Clerestory, Monitor and Sawtooth
Sections and representative light distributions from (A) clerestory, (B) monitor, and (C) sawtooth. For 12:00 noon, clear sky conditions.

7.4.4 Sidelighting Daylight Systems

Sidelighting refers to the act of placing daylight luminaires with vertical glazing in the perimeter walls. Sidelighting schemes have the advantage that they can also provide a view to the exterior, can provide daylight for all floors of multistory buildings, and do not have to penetrate the roof membrane. The downside is that it's more difficult to control glare and to provide uniform lighting since the penetration of daylight is limited to a perimeter band whose width is about two times the height of the windows.

Sidelighting Design Considerations

Penetration of Daylight from Sidelighting

Sidelighting schemes provide daylight levels that are high near the perimeter and fall off rapidly away from the window. As a rough rule of thumb, usable daylight is available at a room depth of 1.5 to 2.5 times the window head height, depending on the design. This dictates relatively high ceiling heights and narrow building sections to fully daylight a building from sidelighting. One technique that allows an elevated window head height without increasing the floor-to-floor height is to slope the ceiling at the perimeter of the space (see Figure 7-20) In effect, the sloping ceiling steals some of the plenum space and leaves less room for HVAC ducts, luminaires and other equipment. But with coordinated design, a full-height plenum can be maintained in the center of the building to adequately serve these purposes.

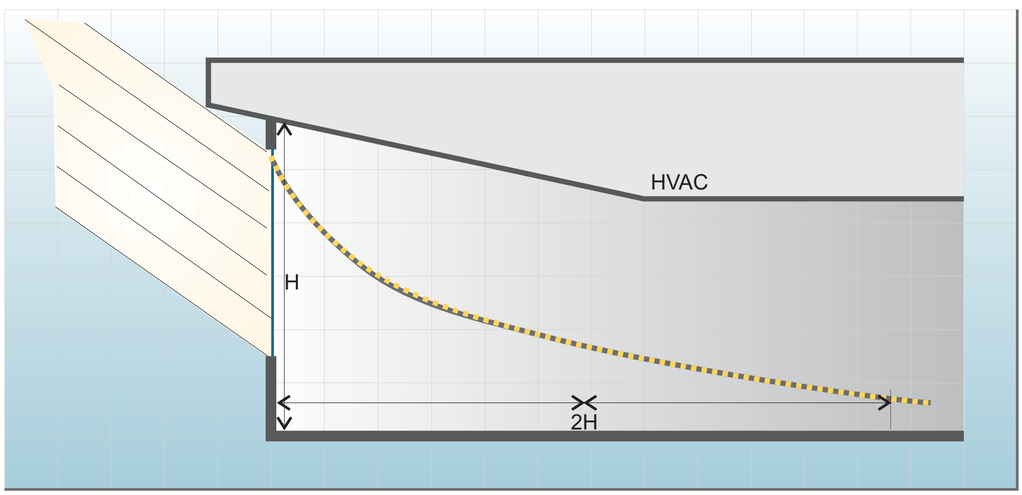


Figure 7-20 – Sidelit Building with Sloped Ceiling at Perimeter
A sloping ceiling at the building perimeter provides a means of elevating the window head to increase daylighting penetration without increasing the floor-to-floor height.

Since daylight "flows" inward from the vertical glazing, closed rooms should be minimized on the perimeter wall. If they can't be avoided, they can share daylight with interior spaces if they have relites on their interior walls. In open-plan areas, partitions, walls and exposed ceiling structural elements should run perpendicular to the window wall. This will enhance the flow of daylight and minimize deep shadows. If partitions must run parallel to the window wall, they should be kept as low as possible or have glass in their upper area. To increase privacy and options for wall space in an open office plan with cubicles, use shorter partitions parallel to the window wall and taller partitions perpendicular to the window wall.

Because of the asymmetrical distribution of daylight from a sidelit scheme, an advanced daylight design combines daylight from two different directions to balance light levels across the space (see Figure 7-21).

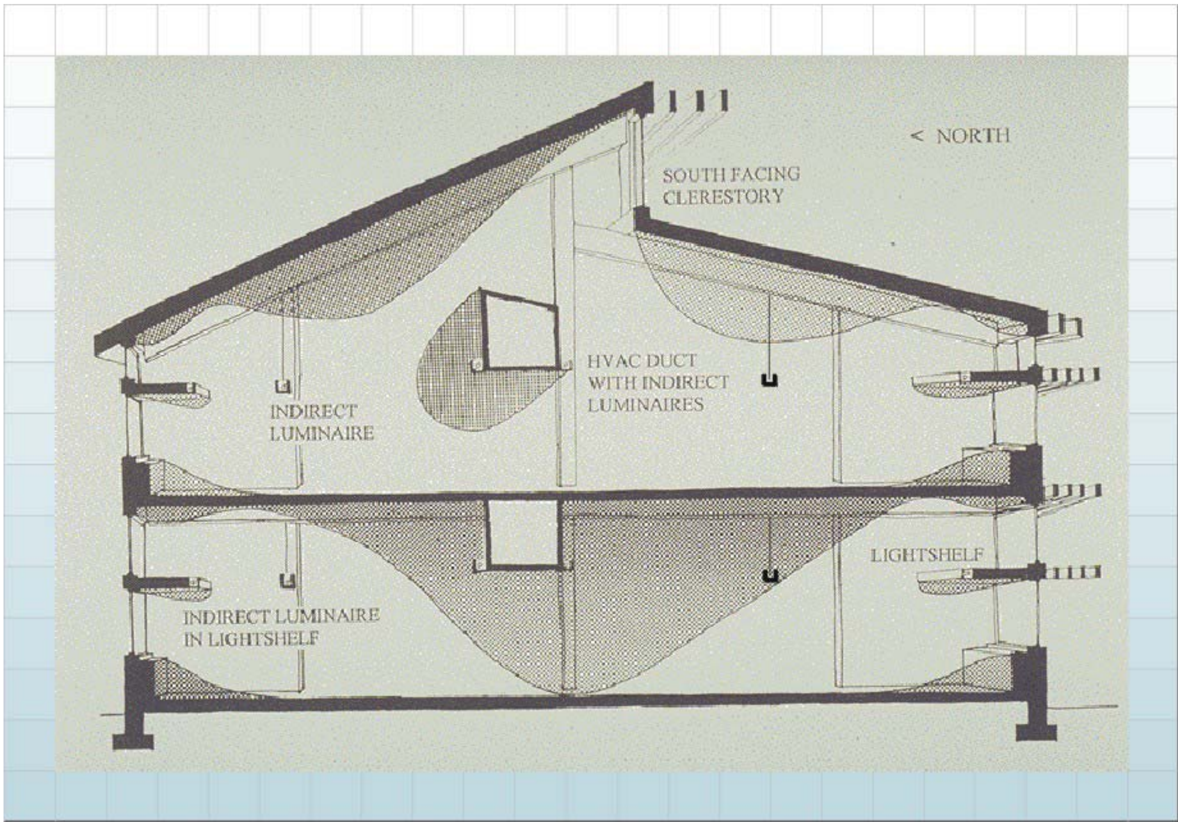


Figure 7-21 – Emerald People's Utility District Building

Top floor of Emerald People's Utility District Building combines north and south sidelighting with a central clerestory to balance daylight across the space. Trellis shades south elevations; lightshelves reflect direct sun (on south elevations) and eliminate glare from the upper glazing (on both north and south).

Sidelighting Orientations

For sidelighting, it's best to elongate the building in the east/west direction and maximize the window area to the south and north. The high south sun angles are easier to shade externally to control for heat gain and glare, and north elevations rarely receive direct sun during normal working hours (only early morning and late afternoon in summer). East and west sun angles, on the other hand, are quite low and difficult to shade, exacerbating solar gain and glare problems.

Direct Sun and Shading Strategies

Direct sun should be excluded from task areas because of the high potential for glare and discomfort. Sun penetration can be controlled by either exterior or interior shading elements (exterior overhangs, louvers, fins, interior blinds, drapes, shades or lightshelves). Exterior shading devices offer the advantage over interior devices because they stop heat gain before it enters the building. The spacing and depth of louvers and overhangs establish a shading or "cutoff angle," defining the sun angles that will be excluded. Tiltable louvers and operable blinds and shades allow more control with an adjustable cutoff angle, but may not be left in their optimal position.

Horizontal overhangs work best with the high sun angles experienced on south facades. East and west facades can use horizontal, vertical or (ideally) a combination of the two in an egg crate pattern. Figure 7-22 shows an example of solar-responsive design of daylight apertures for north and south exposures. Although solar angles are identical in the spring and fall, heating and cooling patterns are not. Since the earth warms up throughout the summer, buildings have higher fall cooling requirements. But permanent, fixed shading devices don't differentiate between spring and fall HVAC needs. Seasonably adjustable shading devices or vegetative shading that increases its foliage from the spring to the fall respond better to actual building needs.

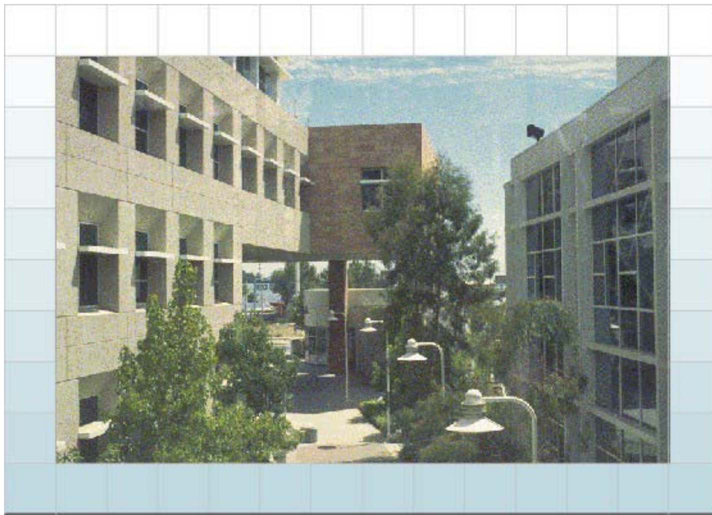


Figure 7-22 – Sidelighting Example, Sacramento Municipal Utility District Building
Solar responsive design of daylight apertures influences the elevations for each solar exposure of these two wings of the Sacramento Municipal Utility District Building. North windows (at right) are large and unshaded. Smaller south windows (at left) are recessed and have exterior lightshelves to shade lower glazing and reflect sunlight deep into the building.

Interior shading devices provide greater user control and are often easier to maintain. Advanced daylighting design provides separate shading controls for view windows and daylight windows. Interior shading devices serve primarily as glare control, although they may also reflect a small proportion of solar heat gain back out the window. Several publications, such as the *Mechanical and Electrical Equipment Handbook* (table 4-19) and the *ASHRAE Handbook,* provide tables of representative shading coefficients for common interior blinds and shading devices.

The depth of the shading device (which defines its cutoff angle) should be designed to minimize solar gain during the cooling season as dictated by window orientation, solar angles at the site, site weather patterns and building internal loads. Shadow patterns from overhangs can be cast manually or with the use of manual tools and computer programs. Several programs are available free online to calculate the degree of protection provided by a particular configuration of window and shading device. Solar-2 (available online at http://www.aud.ucla.edu/energy-design-tools) plots sunlight penetrating through a window including annual tables of percentage window in full sun and radiation on glass. And SUNTECT (available online at http://fridge.arch.uwa.edu.au) is a window-shading design tool that includes sun path diagrams and sun angles. See section 4.4.2 for more information about daylighting design analysis tools.

"Tuning" the Glazing for Each Elevation

Section 7.4.2 describes glazing options that reduce solar gain. Since each building elevation is subjected to different solar gains, an advanced daylighting design may incorporate a different glazing option for each elevation. Some variations of tints and low-e products allow this change in solar performance without noticeable changes in visual appearance. For example, the south elevation of the Sacramento Municipal Utility District Building in Sacramento, California has a lightshelf with clear glazing above and 37% transmission glazing below. The north elevation has larger windows with no lightshelf and glazing that is 49% transmissive.

Sidelighting Options

Punched Windows

Punched windows near eye level are problematic for daylighting because they create high contrast patterns of bright window glazing alternating with darker wall sections. The high contrast causes occupants adjacent to the windows to lower blinds to minimize glare. In addition, if the windows are too far apart, the daylight contours concentrate around each window and do not combine to create a larger electric lighting control zone. To minimize the contrast, wash adjacent surfaces with daylight by splaying the window reveals or locating the punched window directly adjacent to an interior wall. Figure 7-23 shows light level contours for punched windows.

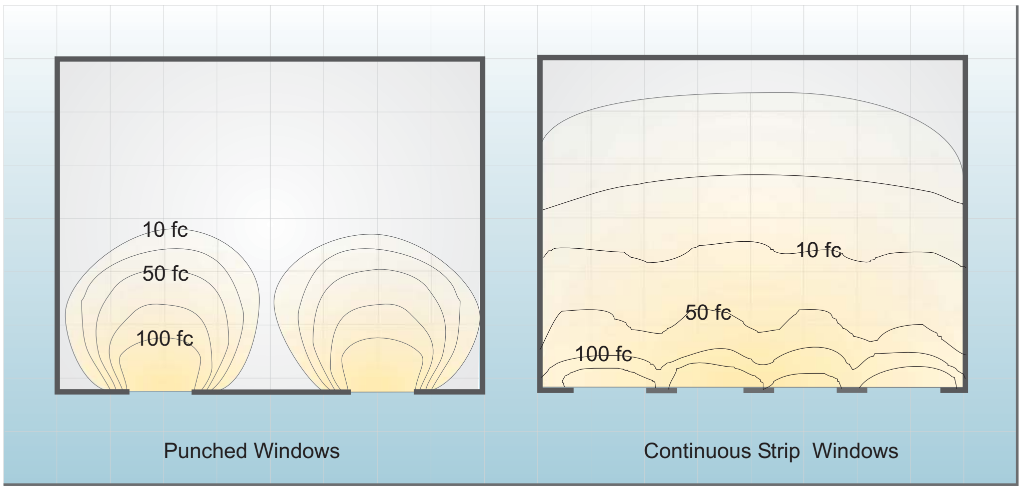


Figure 7-23 – Light Level Contours for Punched Windows and Continuous Strip Window
Light level contours for (A) punched window and (B) continuous strip windows. The punched window wall alternates high bright window areas with dark wall segments. Contours on the continuous window wall add together to create a series of decreasing contours parallel to the window wall.

Continuous Strip Window

Continuous strip windows have become the signature of commercial office building architecture. Although conceptually they can be envisioned with a lower view section and an upper daylighting section, rarely is the shading and glare control differentiated in the two sections. Light level contours run parallel to the window wall and decrease rapidly in intensity away from the window (see Figure 7-23). Usable daylight from a strip window penetrates about 1.5 to 2.0 times the window header height. Although the strip window creates uniform daylight zones parallel to the window wall, individually controlled blinds and shades often disrupt the continuity and detract from the performance of long linear electric lighting control zones.

Advanced strip window designs separate view and daylight portions of the window. Depending on orientation, a lightshelf or louvers (see below) can help to control and redirect daylight from the upper portion of the window. Lower transmission glazing or manually operated interior shades below the lightshelf can be used to control glare at the lower view glazing. Exterior shading devices or selective, low SHGC glazing should also be used to minimize heat gains on solar elevations.

Lightshelves

A lightshelf is a horizontal panel separating the upper and lower windows. Lightshelves work best on south elevations that have relatively high sun profile angles. They are more difficult to design for east and west elevations that encounter low solar angles and require very long lightshelves. North elevations receive very little direct sun, so lightshelves there serve only to block glare from the upper glazing. A lightshelf may be outside the window, inside, or both. The upper glazing may or may not have an exterior overhang or shading device. A well-designed lightshelf serves four distinct functions:

- It separates the window into an upper daylight aperture and a lower view aperture and allows them to be designed optimally to serve these different functions.
- It acts as an overhang to shade the lower glazing and protect against the penetration of direct sunlight into the space. This also serves to balance light distribution in a space by reducing light levels near the perimeter.
- It increases the penetration of daylight into the space by reflecting light from its upper surface onto the ceiling and back into the building. This can increase the usable daylight up to 2.5 times the window head height.
- It extends into the interior to restrict the view of the bright upper glazing, eliminating the potential for glare without the use of blinds, shades or low transmission glazing on the upper window. (Lightshelves on north elevations are used for this reason alone.)

Lightshelves are usually positioned at 7 ft or above, so they require a ceiling height of at least 9.5 ft. They may be made of many different materials (for example, sheetrock, ceiling tiles, translucent fabric or reflective Mylar) but the top surface should be highly reflective to deliver daylight as deep as possible in the space. Most shelves are diffuse reflectors, but some have specular mirrored surfaces. Specular lightshelves reflect direct beam daylight deeper into the space but may also cause distracting streaks of light across the ceiling plane or cause glare in adjacent buildings. Lightshelf materials should be carefully selected to avoid creating overly dark or bright luminous surfaces when viewed from below.

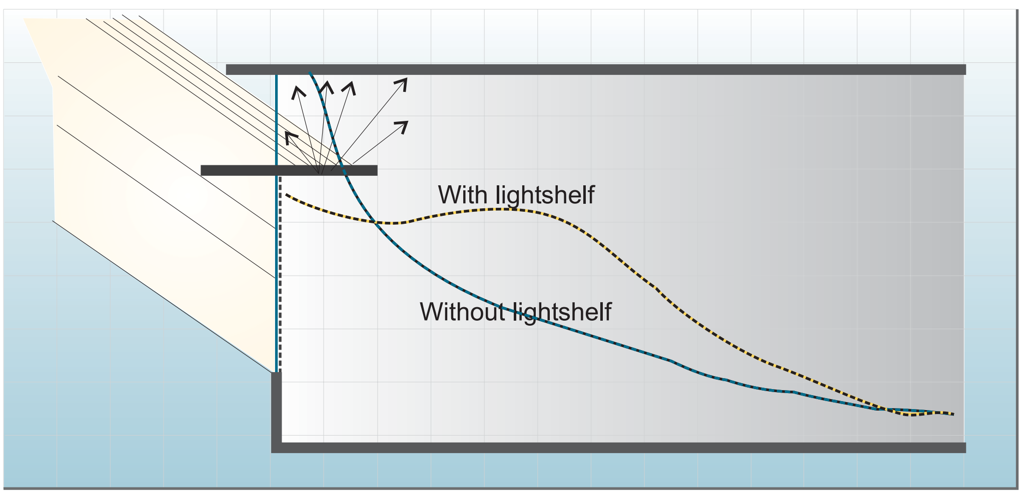


Figure 7-24 – Lightshelf as Indirect Daylight Luminaire

Lightshelves reflect indirect daylight deeper into the space while eliminating glare from the upper glazing. Glare and daylight intensity adjacent to the lower window are minimized with lower glazing transmission and/or adjustable shading devices. The combination of these two increases the depth of daylight penetration and reduces sharp daylight gradients next to the window.

Daylight from the glazing above the lightshelf comes indirectly into the space and uses the ceiling as its secondary reflecting surface. Thus the ceiling should be light colored and diffusely reflecting. High-white reflective ceiling tiles are available from some manufacturers to maximize the daylight reflectance.

The critical specification for the lightshelf is its cutoff angle. The overhang above the upper glazing and the extension of the interior lightshelf below it define a cutoff angle above which direct sun is eliminated from the space (see Figure 7-24). The cutoff angle should be smaller than almost all expected sun angles for that elevation or small enough so that any direct sun that penetrates will hit high in the space above task level and will not cause glare. Lightshelves that are too short will cause unacceptable glare over time and will be retrofit with blinds or shades, compromising their effectiveness.

Both the lightshelf and the glass above it must be cleaned periodically. This can be difficult with wide, fixed shelves. Exterior lightshelves should be sloped slightly to allow rain water and dirt to drain off. Interior lightshelves may need to allow a small gap (6 in. or so) between them and the window wall to allow window washing equipment to be used from below to clean the upper glazing. Care should be exercised to ensure that the lightshelves do not compromise the performance of fire sprinkler systems or HVAC air circulation patterns.

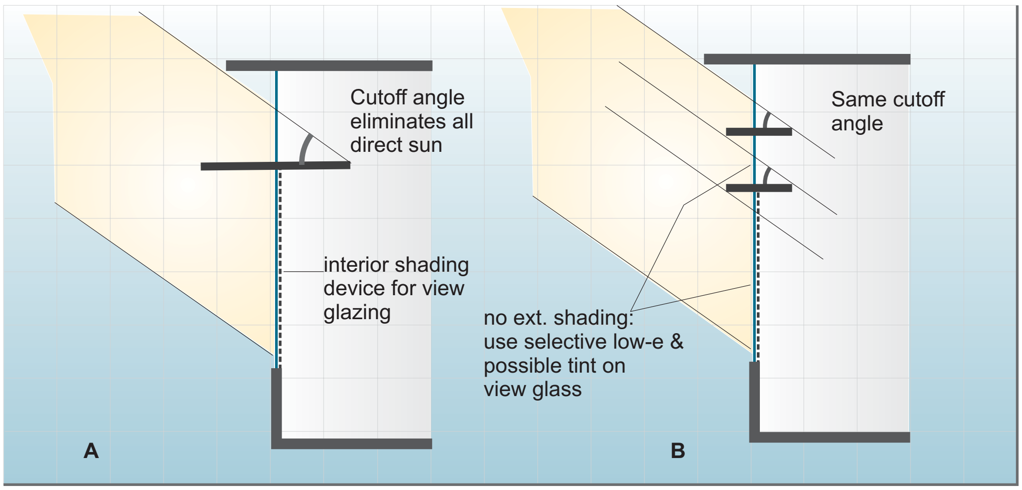


Figure 7-25 – Cutoff Angles for Lightshelf and Louver System
A series of smaller louvers (B) can achieve the same cutoff angle as a lightshelf (A). The lightshelf will perform slightly better, but the louvers are less intrusive on the space.

Louver Systems as a Replacement for Lightshelves

If the calculated cutoff angle requires too deep a lightshelf, a series of fixed or adjustable louvers with the same cutoff angle can be used instead. The use of louvers may also simplify the lightshelf cleaning issues noted above. As the louver dimension is made smaller, they will need to be spaced closer together (to maintain the cutoff angle) and more louvers will be required. This reduces the depth that daylight is delivered in the space. For best optical performance use the largest louvers possible (see Figure 7-25).

Figure 7-26 – Louvers on Clerestory Window

Louvers on this clerestory window at the National Gallery of Canada reflect indirect daylight across the curved ceiling to fill the gallery with soft, low glare ambient light. Photo courtesy Barbara Erwine.

Integration with Electric Lighting

Daylight usually provides ambient lighting in a space, supplemented by electric light where daylight levels are low or when daylight is unavailable. An advanced daylight-integrated electric lighting system will be circuited parallel to the daylight contours and deliver light to the same surfaces as the "daylight luminaires." This allows a natural transition between daylight and electric lighting and simplifies the control scheme. (Section 8.4 – Daylighting Controls discusses strategies for integrating and automatically controlling electric lighting in response to daylight.) For example, as noted above, in continuous strip window buildings, daylight contours run parallel to the window wall, so electric lighting should be circuited parallel to the window wall. Sidelighting that uses louvers or a lightshelf to bounce daylight to the ceiling will uplight the space. This should be integrated with electric light that also has an uplight component.

The following section gives designers a thorough understanding of the light delivery characteristics of electric light luminaires to accomplish a fully integrated lighting design.

7.5 Electric Lighting: Indoor Luminaires

Table 7-3 below, which shows common photometric distributions for luminaires in typical applications, can help guide the lighting designer in selecting the right luminaire for a particular application. This table is followed by detailed information about advanced indoor luminaires. Each luminaire type is accompanied by sketches intended to illustrate representative luminaires and typical photometric distributions for those products.

Various types of luminaires for direct ("downward") lighting are discussed in sections 7.5.2 through 7.5.7. These include recessed and surface-mounted luminaires for ambient lighting; wall-washers, accent lights and display lighting; decorative pendant downward lights; track lighting; task lighting; and shelf lighting. For information about luminaires for indirect lighting ("uplighting"), see section

7.5.8. Section 7.5.9 focuses on direct-indirect ("upward-downward") lighting, while section 7.5.10 covers diffuse lighting.

These sections all focus on features that render the luminaires "advanced." By definition, an advanced lighting system includes higher efficacy lamps and electronic ballasts; these features will not routinely be called out for each luminaire type. Lamps and ballasts are discussed in detail in chapter 6.

7.5.1 Common Light Distributions

Luminaire selection begins by understanding the space, its visual tasks, and its users. From this the lighting designer knows where to put light, and just as importantly, where *not* to put light in order to avoid glare, poor visibility, light trespass and other problems. The designer then selects the luminaire according to its light distribution, depicted graphically by the intensity distribution. Table 7-3 is a guide to many common light distributions and some of their applications. It is by no means a complete list of luminaires or applications, but it covers many typical products and where they are most commonly used. Photometric distributions shown are typical but may not represent the entire range of light distributions available for a type of luminaire. Click on the luminaire type to jump to a discussion of that luminaire in this chapter.

Table 7-3 – Luminaires and Photometric Distributions by Application

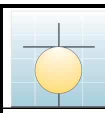
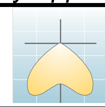
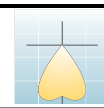
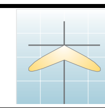
Light Distribution:									
Light Distribution Description:	Downward light with cosine distribution. Poor to moderate glare control.	Downward light with batwing distribution. Good glare control.				Downward light with narrow distribution (often for critical VDT spaces). Good glare control.		Downward light with widespread batwing distribution.	
Luminaire Type: (click to jump to the luminaire section)	Recessed "Indirect" Basket Luminaire	Open HID High-bay Metal Refl.	Recessed Round or Square Downlight	Rec. Parabolic Louver, Narrow, 1-2 Lamp	Rec. Parabolic Louver, Wide, 2-3 Lamp	Rec. Parabolic Louver for Critical VDT Use	Landscape - Tree Downlight	High Performance Roadway	Parking Lot Luminaire
OFFICE									
General, low ceiling, VDT				✓		✓			
General, high ceiling, incl. VDT space									
Cove uplighting, wall-mtd upltg									
Task lighting									
Gnrl, non-VDT:copy rm, lobby, gym etc	✓			✓	✓				
Lobby, waiting space, break area	✓		✓	✓		✓			
Wall-wash, wall accent (VDT&nonVDT)									
SCHOOL									
Classroom gnrl ltg, low ceiling, VDT						✓			
Classroom gnrl ltg, high ceiling, VDT									
Classroom gnrl ltg, non-critical VDT				✓	✓				
Wallboard or corridor wall display									
Lobby, cafeteria, corridor, copy room	✓		✓	✓	✓	✓			
Cove uplighting, wall-mtd upltg									
HOSPITALITY									
Restaurant, ballroom/confrnc, lobby			✓						
Decorative lighting for non-VDT space	✓		✓						
Wall display, perimeter accent									
RETAIL									
General lighting, low ceiling	✓		✓	✓	✓				
General lighting, high ceiling	✓	✓	✓	✓	✓				
Retail or display - accent lighting									
Wall display									
INDUSTRIAL									
Gnrl, non-VDT, warehouse floor, etc.	✓	✓							
Tall, narrow storage aisles		✓							
Localized task lighting									
OUTDOOR									
Facade ltg, tree upltg, signage ltg									
Pathway or stairs						✓		✓	
Recreational sports lighting									
Landscape lighting							✓		
Parking structures									
Canopy									
Parking lot									✓
Roadway and street lighting						✓		✓	

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Table 7-2 – Luminaires and Photometric Distributions by Application Continued from previous page

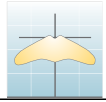
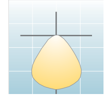
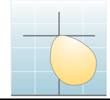
Light Distribution:									
Light Distribution Description:	Mostly downward light with wide, soft batwing distribution.		Downward light with modified cosine distribution.		Downward asymmetrical distribution.				
Luminaire Type: (click to jump to the luminaire section)	Cobra Head	Post-top for Pedestrian Areas	Recessed Lensed Fluor. Troffer	Decorative Pendant Downward	Track Lighting - Fluorescent	Task Ltg - Fixed & Furn. Integrated	Task Ltg - Portable	Building Exterior Wall Sconce	Wall-mtd Exterior Sconce & Wallpack
OFFICE									
General, low ceiling, VDT									
General, high ceiling, incl. VDT space									
Cove uplighting, wall-mtd upltg									
Task lighting						✓	✓		
Gnrl, non-VDT:copy rm, lobby, gym etc			✓						
Lobby, waiting space, break area			✓	✓					
Wall-wash, wall accent (VDT&nonVDT)					✓				
SCHOOL									
Classroom gnrl ltg, low ceiling, VDT									
Classroom gnrl ltg, high ceiling, VDT									
Classroom gnrl ltg, non-critical VDT			✓						
Wallboard or corridor wall display					✓				
Lobby, cafeteria, corridor, copy room			✓						
Cove uplighting, wall-mtd upltg									
HOSPITALITY									
Restaurant, ballroom/confrnc, lobby									
Decorative lighting for non-VDT space				✓					
Wall display, perimeter accent					✓				
RETAIL									
General lighting, low ceiling			✓	✓					
General lighting, high ceiling			✓						
Retail or display - accent lighting									
Wall display					✓				
INDUSTRIAL									
Gnrl, non-VDT, warehouse floor, etc.			✓						
Tall, narrow storage aisles			✓						
Localized task lighting			✓			✓	✓		
OUTDOOR									
Facade ltg, tree upltg, signage ltg									
Pathway or stairs		✓						✓	✓
Recreational sports lighting									
Landscape								✓	
Parking structures									
Canopy									
Parking lot									
Roadway and street lighting	✓	✓							

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Table 7-2 – Luminaires and Photometric Distributions by Application Continued from previous page

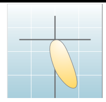
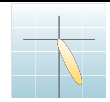
Light Distribution:												
Light Distribution Description:	Downward asymmetrical wall-wash distribution.							Narrow beam downward accent light.				
Luminaire Type: (click to jump to the luminaire section)	Chalkboard or Whiteboard	Recessed Round Wall-washer	Recessed Wall Slot	Signage Luminaire	Building Facade Luminaire	Wall-washer – Recessed Round	Recessed Linear Wall-washer	Recessed Accent - MR-16	Recessed Accent - MH PAR	Track Lighting - Incandescent	Track Lighting - Metal Halide	Recreational Sports Lumin.
OFFICE												
General, low ceiling, VDT												
General, high ceiling, incl. VDT space												
Cove uplighting, wall-mtd upltg												
Task lighting												
Gnrl, non-VDT:copy rm, lobby, gym etc												
Lobby, waiting space, break area												
Wall-wash, wall accent (VDT&nonVDT)	✓	✓	✓			✓	✓	✓	✓	✓	✓	
SCHOOL												
Classroom gnrl ltg, low ceiling, VDT												
Classroom gnrl ltg, high ceiling, VDT												
Classroom gnrl ltg, non-critical VDT												
Wallboard or corridor wall display	✓	✓	✓			✓	✓					
Lobby, cafeteria, corridor, copy room												
Cove uplighting, wall-mtd upltg						✓	✓					
HOSPITALITY												
Restaurant, ballroom/confrnc, lobby												
Decorative lighting for non-VDT space												
Wall display, perimeter accent	✓	✓	✓			✓	✓	✓	✓	✓	✓	
RETAIL												
General lighting, low ceiling												
General lighting, high ceiling												
Retail or display - accent lighting								✓	✓	✓	✓	
Wall display	✓	✓				✓	✓					
INDUSTRIAL												
Gnrl, non-VDT, warehouse floor, etc.												
Tall, narrow storage aisles												
Localized task lighting									✓	✓	✓	
OUTDOOR												
Facade ltg, tree upltg, signage ltg				✓	✓							
Pathway or stairs												
Recreational sports lighting												✓
Landscape lighting												
Parking structures												
Canopy												
Parking lot												
Roadway and street lighting												

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Table 7-2 – Luminaires and Photometric Distributions by Application Continued from previous page

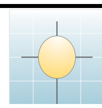
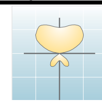
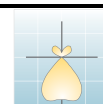
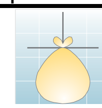
Light Distribution:									
Light Distribution:	Diffuse lighting. Poor glare control.		Mostly uplight. Good glare control.		Mostly downlight. Good glare control.		Mostly downlight. Moderate glare control.		
Luminaire Type: (click to jump to the luminaire section)	Decorative - Pendant	Decorative - Sconce	Suspended Dir-Indirect Lin. Fluor.	Decorative Dir-Indirect Pendant	Open HID Hi-bay Glass/Plas. Refl.	Suspended Dir-Indirect Lin. Fluor.	Open Fluor. - Refl. Industrial	Lensed HID Low-bay	Lensed Fluor. Low-bay
OFFICE									
General, low ceiling, VDT			✓	✓					
General, high ceiling, incl. VDT space			✓	✓		✓			
Cove uplighting, wall-mtd upltg									
Task lighting									
Gnrl, non-VDT:copy rm, lobby, gym etc			✓	✓	✓	✓			
Lobby, waiting space, break area	✓	✓	✓	✓	✓	✓			
Wall-wash, wall accent (VDT&nonVDT)									
SCHOOL									
Classroom gnrl ltg, low ceiling, VDT			✓	✓					
Classroom gnrl ltg, high ceiling, VDT			✓	✓		✓			
Classroom gnrl ltg, non-critical VDT			✓	✓		✓			
Wallboard or corridor wall display									
Lobby, cafeteria, corridor, copy room	✓	✓	✓	✓		✓			
Cove uplighting, wall-mtd upltg									
HOSPITALITY									
Restaurant, ballroom/confrnc, lobby				✓					
Decorative lighting for non-VDT space	✓	✓	✓	✓					
Wall display, perimeter accent									
RETAIL									
General lighting, low ceiling									
General lighting, high ceiling					✓	✓	✓	✓	✓
Retail or display - accent lighting									
Wall display									
INDUSTRIAL									
Gnrl, non-VDT, warehouse floor, etc.					✓		✓	✓	✓
Tall, narrow storage aisles					✓		✓		
Localized task lighting									
OUTDOOR									
Facade ltg, tree upltg, signage ltg									
Pathway or stairs									
Recreational sports lighting									
Landscape lighting									
Parking structures									
Canopy									
Parking lot									
Roadway and street lighting									

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Table 7-2 – Luminaires and Photometric Distributions by Application Continued from previous page

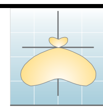
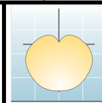
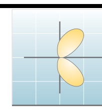
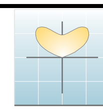
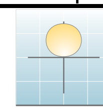
Light Distribution:									
Light Distribution Description:	Widespread mostly downlight. Moderate glare control.			Mostly downlight. Poor glare control.	Wall-mtd. up/down light. Good glare control.	Widespread uplight.		Cosine uplight.	
Luminaire Type: (click to jump to the luminaire section)	Fluorescent Wraparound	Parking Structure Luminaire	Canopy Luminaire	Open Fluorescent - Striplight	Wall-mtd Valance or Sconce	Suspended Linear Fluor.	Decorative Indirect Pendant	Suspended Linear Fluor.	Portable Torchiere Uplight
OFFICE									
General, low ceiling, VDT					✓	✓	✓		
General, high ceiling, incl. VDT space					✓	✓	✓	✓	✓
Cove uplighting, wall-mtd upltg									
Task lighting									
Gnrl, non-VDT:copy rm, lobby, gym etc	✓				✓	✓	✓	✓	✓
Lobby, waiting space, break area					✓	✓	✓	✓	✓
Wall-wash, wall accent (VDT&nonVDT)									
SCHOOL									
Classroom gnrl ltg, low ceiling, VDT					✓	✓	✓		
Classroom gnrl ltg, high ceiling, VDT					✓	✓	✓	✓	✓
Classroom gnrl ltg, non-critical VDT					✓	✓	✓	✓	✓
Wallboard or corridor wall display									
Lobby, cafeteria, corridor, copy room	✓				✓	✓	✓	✓	✓
Cove uplighting, wall-mtd upltg									
HOSPITALITY									
Restaurant, ballroom/confrnc, lobby						✓	✓	✓	✓
Decorative lighting for non-VDT space					✓		✓	✓	✓
Wall display, perimeter accent									
RETAIL									
General lighting, low ceiling									
General lighting, high ceiling				✓		✓	✓	✓	✓
Retail or display - accent lighting									
Wall display									
INDUSTRIAL									
Gnrl, non-VDT, warehouse floor, etc.				✓					
Tall, narrow storage aisles									
Localized task lighting									
OUTDOOR									
Facade ltg, tree upltg, signage ltg									
Pathway or stairs									
Recreational sports lighting									
Landscape lighting									
Parking structures		✓		✓					
Canopy			✓						
Parking lot									
Roadway and street lighting									

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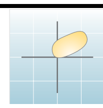
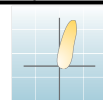
Table 7-2 – Luminaires and Photometric Distributions by Application Continued from previous page

Light Distribution:						
Light Distribution Description:	Asymmetrical uplight		Asymmetrical uplight for wall-wash or accent			
Luminaire Type: (click to jump to the luminaire section)	Wall-mounted Uplighting	Cove Uplighting	Landscape – MH Uplight	Landscape – Well Uplight	Landscape - Underwater	Building Facade - Uplight
OFFICE						
General, low ceiling, VDT						
General, high ceiling, incl. VDT space						
Cove uplighting, wall-mtd upltg	✓	✓				
Task lighting						
Gnrl, non-VDT:copy rm, lobby, gym etc						
Lobby, waiting space, break area	✓	✓				
Wall-wash, wall accent (VDT&nonVDT)						
SCHOOL						
Classroom gnrl ltg, low ceiling, VDT						
Classroom gnrl ltg, high ceiling, VDT	✓	✓				
Classroom gnrl ltg, non-critical VDT						
Wallboard or corridor wall display						
Lobby, cafeteria, corridor, copy room	✓	✓				
Cove uplighting, wall-mtd upltg	✓	✓				
HOSPITALITY						
Restaurant, ballroom/confrnc, lobby	✓	✓				
Decorative lighting for non-VDT space	✓	✓				
Wall display, perimeter accent						
RETAIL						
General lighting, low ceiling						
General lighting, high ceiling	✓	✓				
Retail or display - accent lighting						
Wall display						
INDUSTRIAL						
Gnrl, non-VDT, warehouse floor, etc.						
Tall, narrow storage aisles						
Localized task lighting						
OUTDOOR						
Facade ltg, tree upltg, signage ltg			✓	✓		✓
Pathway or stairs						
Recreational sports lighting						
Landscape lighting			✓	✓	✓	
Parking structures						
Canopy						
Parking lot						
Roadway and street lighting						

7.5.2 Direct ("Downward") Lighting: Luminaires for Ambient Lighting

Recessed or surface-mounted luminaires for ambient lighting are discussed in this section. These luminaires include:

- Lensed fluorescent troffers
- Parabolic louver fluorescent troffers
- Parabolic louver fluorescent troffers for critical VDT applications
- Recessed "indirect" (perforated metal basket)
- Open HID "high-bay"—metal reflector
- Recessed round or square downlights

LENSED FLUORESCENT TROFFERS

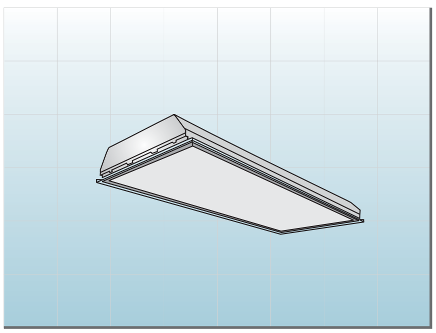


Figure 7-27 – Lensed Fluorescent Troffer

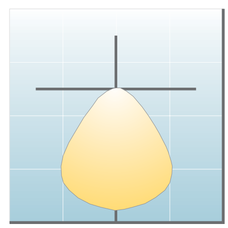


Figure 7-28 – Typical Photometric Distribution for Lensed Fluorescent Troffer

Description: Troffers are luminaires that are usually ceiling-mounted or recessed into a lay-in grid ceiling, usually 1 ft x 4 ft, 2 ft x 4 ft, or 2 ft x 2 ft in size. The features described below enable superior photometric performance.

Lamping: Use no more than three T-8 lamps per 2 ft x 4 ft luminaire, in order to minimize trapped heat that reduces the thermal factor. See section 6.5

Materials: High reflectance white paint on the reflector surfaces improves efficiency. Reflectances of 0.92 or greater are possible. Specular metal reflectors do not dramatically improve efficiency, although they may improve the evenness of the light across the prismatic lens.

Acrylic prismatic lenses should obscure the lamp images, so that lamp "stripes" are not noticeable through the lens. The lenses should also limit luminous intensity (and therefore, glare) at angles above 60 degrees, while maintaining a transmittance of 85% or more. One such technology is called "reverse apex technology," where the top portion of the prism is inverted. The imaging properties of the prisms oriented in opposite directions allow greater dispersion of the light.

Operation and Maintenance: Look for gasketing in the door frame to minimize the amount of dirt accumulated in the luminaire, or a door frame design that is sufficiently snug to minimize dust and insect infiltration.

Efficiency: Luminaire efficiencies of greater than 80% are possible.

Design and Control Considerations: In three-lamp troffers, the outer lamps may be switched separately from the center lamp if the center lamp is tandem-wired to a nearby luminaire (see chapter 8). Lensed luminaires are very good at spreading light evenly through a room and helping walls look bright, but the lens may be too bright to view directly or when reflected in a computer screen.

PARABOLIC LOUVER FLUORESCENT TROFFERS

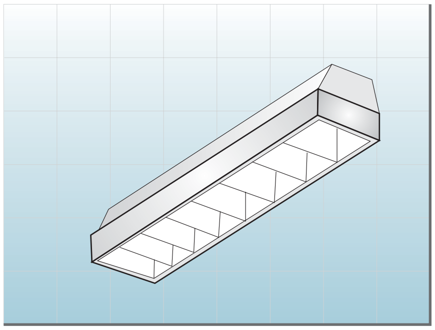


Figure 7-29 – Parabolic Louver Fluorescent Troffer, 1x4 Baffle

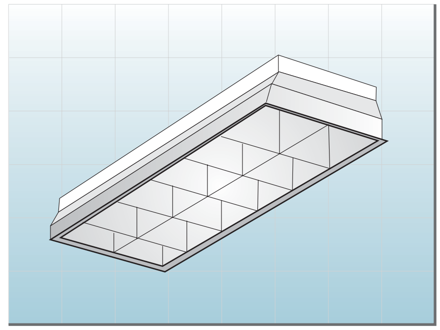


Figure 7-30 – Parabolic Louver Fluorescent Troffer, 2x4 Louver

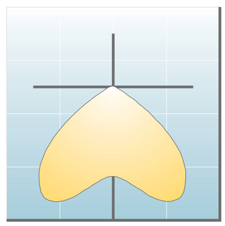


Figure 7-31 – Typical Photometric Distribution, Parabolic Louver Fluorescent Troffer

Description: The parabolic louver differs from a lens in that it uses vertical blades to block the view of the lamps at normal viewing angles. The louvers also redirect light to the sides to minimize reflected glare and improve work plane uniformity.

Lamping: Viewers can occasionally see the bright bare lamps between the louver blades, so it's advisable to use fluorescent lamps that are no smaller in diameter than T-8. Smaller lamps exceed 1,700 cd/ft² in luminance, and are likely to cause discomfort if they can be viewed directly, or if users sit beneath them for an extended period of time. See section 6.5.

Materials: Two typical materials and four typical finishes are used for parabolic louvers.

Typical Materials:

- *Small-cell plastic louvers* with a vacuum-deposited metal finish. Luminaires using these ½ in. or 1-in. tall louvers are not recommended for ambient lighting because the small cell size usually equates to very low luminaire efficiencies. Plus they tend to have an electrostatic attraction to dirt particles. Use these only for specialized applications.
- *Large-cell aluminum louvers.* These usually have a cell depth of 1.5–4 in. Depending on the shielding angle (Figure 7-32), these can be very effective solutions for a wide range of applications, from supermarkets to VDT offices. The louver finishes are: specular, semi-specular, matte aluminum and white-painted aluminum.

Typical Finishes:

Specular Louvers. These can control light very precisely, appear dark from a distance, and are often used in VDT-critical applications. However, the louvers tend to "flash," suddenly going from a dark to very bright appearance as the viewer moves into its lighted zone. Specular finish parabolics usually produce pronounced scalloped light patterns on walls. Without additional dedicated wall-washing luminaires, rooms lit with these can look like caves, and faces are modeled with harsh shadows.

Semi-Specular Aluminum Louvers. These have an etched or brushed appearance. This produces a softer edge to the light distribution that mitigates the cave effect and annoying flash of specular louvers. If these luminaires are mounted within 3 ft of walls, they can provide some desirable brightness on the wall. The softer distribution helps faces look more pleasant. Because the luminaire is “brighter” in appearance, it may produce somewhat poorer seeing conditions for viewing computer screens.

Matte Aluminum Louvers. These are also semi-specular louvers, but with a lighter, more diffuse appearance.

White-Painted Aluminum Louvers. These have a cheerful, light appearance. They brighten walls and help provide light on faces and objects in the space. They are an excellent choice in corridors, retail spaces and copy rooms, but will cause reflected image in all but the best quality computer screens.

Operation and Maintenance: Louver material and finish affects how much dust the louver attracts and how easy louvers are to clean. (See louver descriptions, above.)

Efficiency: Usually greater than 65% for a 1-lamp, 12 in. wide luminaire; greater than 70% for a 12 to 24 in. wide 2-or 3-lamp luminaire.

Design and Control Considerations: Look for a louver shielding angle greater than 30 degrees, so that users are not normally seeing bright, bare lamps. See Figure 7-32. Choose louvers that do not produce offensively bright “flashes” of light as the user moves relative to the luminaire. This problem is unfortunately hard to tell from a standard photometric report, but it occurs more often in luminaires with a very sharp cutoff angle below which the luminaire is emitting very high intensities of light, but above which its intensity drops to almost nothing. In offices, consider dimming ballasts and controls which allow an office worker to customize the output of the luminaire above his or her workstation (see chapter 8).

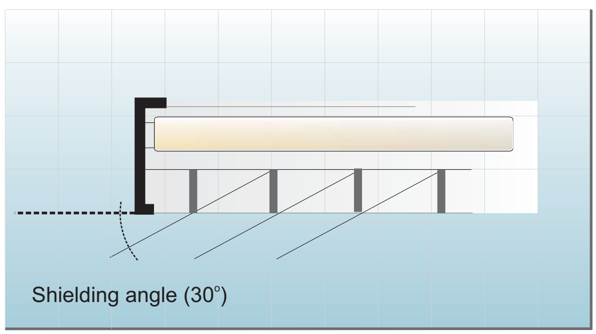


Figure 7-32 – Louver Shielding Angle

PARABOLIC LOUVER FLUORESCENT TROFFERS FOR CRITICAL VDT APPLICATIONS

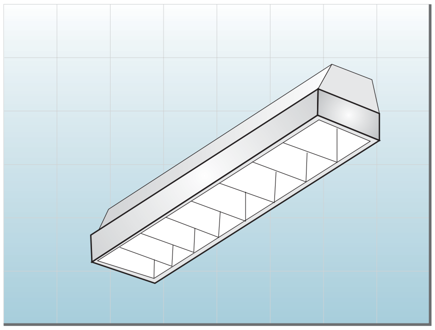


Figure 7-33– Parabolic Louver Fluorescent Troffer for Critical VDT Applications

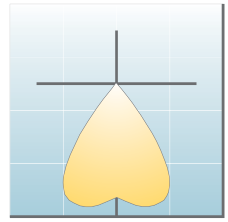


Figure 7-34 – Typ. Photometric Dist., Parabolic Louver Fluor. Troffer, Critical VDT Application

Description: Luminaires for critical VDT applications are similar to parabolics described above, but they may be narrower and use fewer lamps. They are also especially effective in limiting luminous intensity in vertical angles from 55 to 90 degrees. The reflected image of the lighted louver on the computer screen is low in brightness, and interferes less with the characters or graphics on the screen.

Lamping: See “Parabolic Louver Fluorescent Troffer” above.

Materials: See specular, semi-specular, and matte finish louvers in “Parabolic Louver” above.

Operation and Maintenance: See “Parabolic Louver” above.

Efficiency: Usually greater than 60% for a 1-lamp, 6-12 in. wide luminaire; greater than 65% for a 12 to 24 in. wide 2-or 3-lamp luminaire.

Design and Control Considerations: A luminaire’s luminous intensity (candlepower) is a convenient metric with which to judge the potential brightness of the luminaire. In VDT-intensive spaces, where the computer screen is the principal and critical visual task, the luminaire should not emit more than 300 candelas at any angle that will be reflected in the computer screen. For traditional vertically oriented screens, this means limiting the luminaire’s intensity from 55 to 90 degrees. If computer screens are nearly flat or horizontal, the designer can calculate the angles at which the light from the luminaire is likely to reflect in the screen, and choose luminaires with low candlepower emitted at those angles.

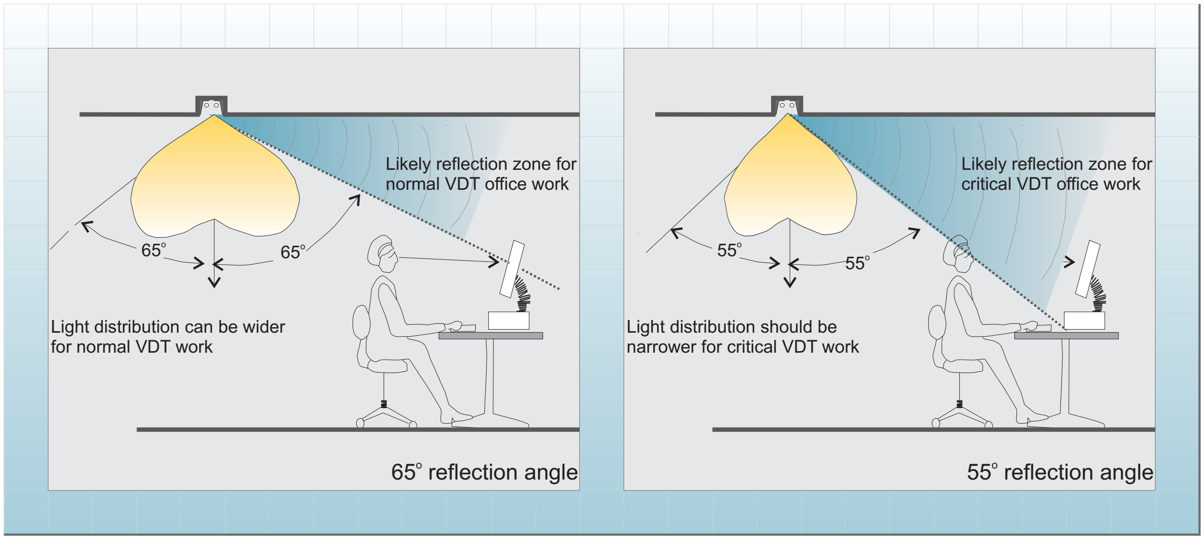


Figure 7-34 – Critical VDT Viewing Angles

If excellent-quality computer screens are used, almost any luminaire will produce acceptable viewing conditions, so the luminaire need not meet the conditions described above. (As of this writing the new IESNA RP-1 Recommended Practice on office lighting is in process. Consult the completed document, expected in 2001, for more information on luminous intensity limits and screen selection.) It is of course still important to consider direct glare and other quality issues in selecting the lighting system.

RECESSED "INDIRECT" (PERFORATED METAL BASKET LUMINAIRE)

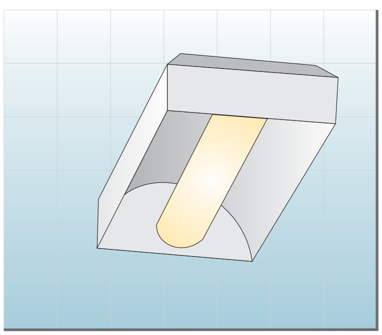


Figure 7-35 – Recessed "Indirect" Luminaire

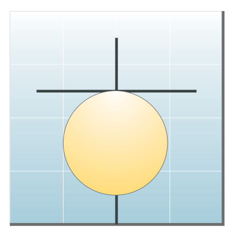


Figure 7-36 – Typical Photometric Distribution for Recessed "Indirect" Luminaire

Description: This genre of luminaire is difficult to name because its light is really directed downward from the ceiling plane. The luminaire is recessed or semi-recessed with a white-painted reflector above the ceiling. This reflector redirects light from lamps concealed in a perforated metal “basket” suspended from it, at the plane of the ceiling or just below the ceiling. The perforations allow a gentle glow of downward light without allowing a direct view of the T-8 or compact fluorescent lamps. Variations on this luminaire include a basket with parabolic baffles for downlight, baskets located at the edges of the 2 ft x 2 ft or 2 ft x 4 ft housing, and surface-mounted versions.

Lamping: T-8 and T-5 linear fluorescent, and FT compact fluorescent lamps work well. See section 6.5.

Materials: Look for matte paint or metallic finishes on the reflector. If it doesn't have a matte finish, people may see a glaring reflection of the lamp in the reflector.

Operation and Maintenance: Check that the product is easy to relamp and that ballast access is not labor intensive.

Efficiency: Look for luminaire efficiencies exceeding 60%.

Design and Control Considerations: Although the luminaire is low in brightness from any angle for the viewer, its light distribution is usually a soft “blob” or “cosine.” It lights walls, shelves, racks and faces well. It’s an excellent solution for corridors, retail shops with flexible merchandise, medical procedure rooms, and spaces without long-term computer use.

OPEN HID “HIGH-BAY”—METAL REFLECTOR

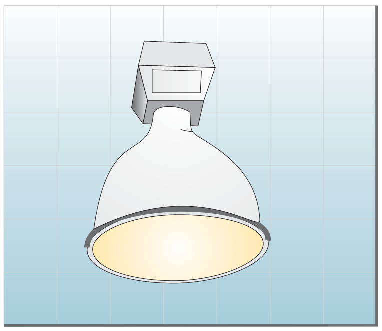


Figure 7-37 – Open HID High-bay (Metal Reflector) Luminaire

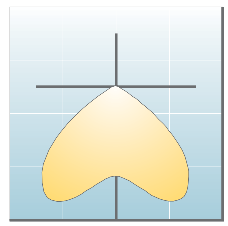


Figure 7-38 – Typical Photometric Distribution, Open HID High-bay (Metal Reflector) Luminaire

Description: Open HID luminaires for utilitarian industrial applications or big box retail most often use a spun-aluminum reflector to direct light from the metal halide or high-pressure sodium lamp. They have a relatively narrow downward light distribution, best described by the spacing criterion. They are intended for mounting in tall spaces (SC = 1.0–1.7), usually with a mounting height greater than 16 ft.

Lamping: Use coated lamps to reduce the glare of the bare lamp, and reduce flicker from clear metal halide lamps. If using metal halide lamps, consider pulse-start lamps for higher efficiency, longer life, and better lumen maintenance. See section 6.6.

Materials: The interior of the reflector is polished for high light reflectance and good optical control.

Operation and Maintenance: The reflector may allow up to 20% of uplight onto the ceiling, which helps reduce the user’s perceived glare of the luminaire, and which contributes bounced light that helps reduce sharp shadows in the space. It also encourages convective currents that keep the reflectors cleaner. Locate luminaires where they can be easily accessed with lifts or ladder for maintenance.

Efficiency: Efficiencies often exceed 80%, while emitting less than 10% of the luminaire’s lumens between 60 and 90 degrees.

Design and Control Considerations: Look for bilevel systems that allow two light levels from the metal halide or high-pressure sodium lamps when the space is unoccupied. Also called a “hi-lo” system, this system warms the lamp for several minutes when switched on at the beginning of the shift (for more about hi-lo systems, see sections 6.6.6 and 8.1.3). Once the lamp is stabilized, the ballast drops the light output of the lamp to 25–50% if no occupancy is detected in the area (for example, a warehouse aisle). The light output idles at the low level until occupancy is detected, and the light output is brought to 100% output within seconds.

This system can also be used in conjunction with a photosensor in a skylit space, for example. It drops to the lower level if daylight is detected. The color rendering of the metal halide lamp drops considerably when idling at the low level, but this is seldom a problem if no one is there to see it, or if there is plentiful daylight to compensate.

RECESSED ROUND OR SQUARE DOWNLIGHTS

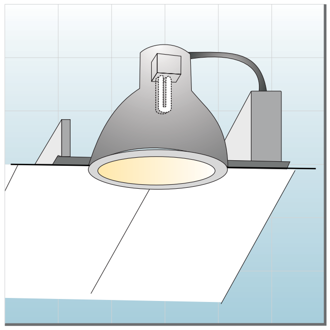


Figure 7-39 – Recessed Round Downlight

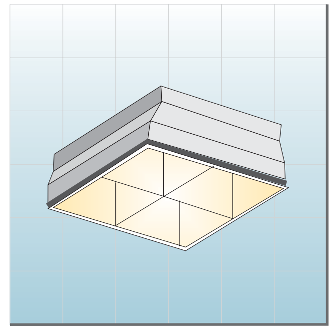


Figure 7-40 – Recessed Square Downlight

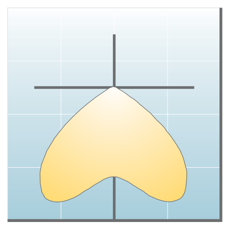


Figure 7-41 – Typical Photometric Distribution, Recessed Round or Square Downlight

Description: The best recessed downlights produce the desired light distribution while minimizing glare and maximizing efficiency. Three types of downlight luminaires are described in this section: incandescent (halogen), compact fluorescent and HID. (See chapter 6 for detailed information about each of these sources.)

Lamping: Advanced downlights may use halogen, compact fluorescent, electrodeless fluorescent or HID lamps. Halogen downlights are typically used for dramatic effect or ease of dimming (as in high-end retail space or a restaurant). However, halogen lamp life is short and efficacy is poorer than other source options, so advanced design will use halogen downlights only in very special spaces.

Materials: Reflector “cone” finishes affect efficiency. (The cone is the lower part of the optics, at the ceiling aperture.) In general, white, specular or matte-finish aluminum produces high efficiency; anodized finishes such as “pewter,” “wheat,” “gold” or “copper” are less efficient because they absorb some light while they color the appearance of the cone; black aluminum or ridged black inner rings, also called “black baffles,” are very low brightness in appearance, but are least efficient.

Operation and Maintenance: Specify downlights that are easy to relamp and change out the ballast or transformer when necessary.

Efficiency: See listing by lamp type below.

Design and Control Considerations: Recessed downlights for ambient lighting have applications in corridors, lobbies, restaurants, retail sales spaces and other similar spaces. They should be used cautiously in offices and long-term workspaces because they may cast strong shadows on faces and task areas. Bear in mind that if the aperture is large, then bare lamps may be easy to see and will be a cause of discomfort or overhead glare. Fresnel or prismatic lenses can reduce this glare by spreading across a larger area; this is a good idea as long as luminaire efficiency or maintainability are not significantly impaired.

The optical systems of advanced downlights should control the light so that bare lamps and their reflected images are not visible or uncomfortable for users. Better quality luminaires are often deeper, allowing the lamp(s) to be recessed several inches above the ceiling plane. Shallower luminaires can accomplish the same thing with cross-baffles or louvers that block the normal view of the lamp. The 1 ft x 1 ft parabolic downlight for compact fluorescent lamps is extremely efficient, providing an efficient alternative to incandescent downlights at one-fourth the power, while in some applications being more aesthetically appealing than full-size fluorescent systems.

There are often several optical systems available for a given lamp type. This allows the specifier to choose a narrow (SC < 0.7), medium (SC = 0.8–1), or wide (SC > 1) light distribution.

Considerations and advanced features for downlights with specific lamp types include:

- Incandescent (halogen) lamps:

Look for efficiencies greater than 70% for A-lamp halogen downlights; greater than 90% for PAR-38 or PAR-30 halogen downlights; greater than 60% for MR-16 downlights.

- Compact fluorescent lamps (CFL):

Advanced luminaires take the thermal conditions of the lamp into consideration, providing apertures for venting or other means to ensure trapped heat will not degrade the light output of the installed luminaire. When the luminaire must be enclosed, consider using amalgam lamps (see section 6.5.6) that remain high in output in high ambient temperature conditions.

Consider using four-pin CFLs with electronic ballasts. These lamps can be dimmed down to 5–10% of maximum if specified with dimmable electronic ballasts and compatible controls. The dimming saves energy as well as providing flexibility for different moods or tasks.

When using horizontal lamps, luminaires with lamps tipped a few degrees downward from horizontal enables maximum light output.

Look for luminaire efficiencies greater than 55% for 2- to 26-watt CF open downlights; greater than 60% for 32 watt CF open downlights; greater than 40% for lensed CF downlights; and greater than 50% for 1 ft x1 ft square, 4-cell parabolic downlights.

- HID lamps:

Metal halide lamps include: reflectored (for example, PAR shapes); compact single-ended plug-base; double-ended; or screw-base. Some of these lamps require additional protective glass enclosure in the luminaire to contain the lamp shards in the unlikely event of a dramatic lamp failure. Remember that this glass needs to be easily removable for relamping. PAR-shaped lamps and “protected” E-shaped lamps don’t require additional shielding, and are a good option for areas where pole-relamping is needed. PAR lamp downlights are often smaller and less complex than their equivalent E-shaped lamps because the optics are contained within the lamp itself. Compact single-ended and double-ended lamps enable high optical precision in a small luminaire, but relamping is often more difficult because of the protective glass.

The specifier should keep in mind that the arc tube of the bare metal halide lamp is offensively bright and should be shielded from normal view. This means the luminaire depth and aperture size should be such that the arc tube is recessed deeply into the downlight, or there should be a diffusing Fresnel or prismatic lens to spread the arc tube brightness over a larger area. PAR lamps usually spread the brightness across the face of the lamp, doing a good job of reducing the perceived brightness.

Clear lamps amplify imperfections in unlensed optical systems, resulting in bright rings on the ground below the luminaire, or peculiar striations if the light strikes a wall. White reflectors or reflectors that are hammered or “peened” can help smooth out the resulting light pattern, but the most common solution for HID downlights is to use coated lamps. The resulting circle of light on the floor has a more uniform field, and has a softer edge to the beam.

Whenever possible, specify electronic ballasts for best performance in terms of audible noise, flicker, color consistency, and reduced weight. Electronic ballasts are more expensive and only widely available for metal halide lamps from 39 W up to 150 W at the time of this writing. However, they are a worthy choice for higher wattage lamps when they become available. See section **6.5.3** for a detailed discussion of electronic ballasts.

The following efficiencies are achievable: 90% for a 39–70 W PAR-20 or PAR-30 MH downlight; 60% for a 70–175 W E-17 MH downlight; 40% for a 400 W BT-37 MH downlight.

7.5.3 Direct ("Downward") Lighting: Wall-washers, Accent Lights, Display Lighting

These luminaires, which are described below, include:

- Recessed linear wall-washers
- Chalkboard or whiteboard lighting
- Recessed round wall-washers
- Recessed wall slots
- Recessed accent lights, incandescent and metal halide

RECESSED LINEAR WALL-WASHERS

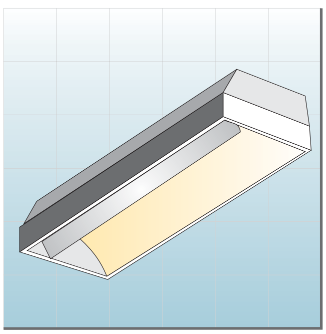


Figure 7-42 – Recessed Linear Wall-washer

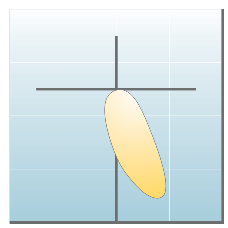


Figure 7-43 – Typical Photometric Distribution, Recessed Linear Wall-washer

Description: These luminaires are usually 8–12 in. wide with a specular or semi-specular asymmetrical reflector designed to spread light evenly on walls in offices, retail stores, schools, etc., with very modest power usage. Common lengths are 2 ft and 4 ft.

Lamping: They usually use T-8 or long twin-tube compact fluorescent lamps. See section 6.5.

Materials: Reflectors are often combinations of specular, semi-specular, and painted white metal.

Operation and Maintenance: Specular reflectors can show fingerprints more readily than other materials.

Efficiency: Efficiencies of more than 45% are available.

Design and Control Considerations: Normally these are spaced so that the side closest to the wall is 2–3 ft from that wall, allowing a very uniform wash of light from top to bottom. If the transition from high to low illuminance on the wall is smooth, ratios as high as 10 to 1 can be visually acceptable. In retail applications, lower ratios of 3 to 1 or 4 to 1 may help the shopper see merchandise at the base of the wall display more easily.

Glare control is often an issue if users or shoppers normally walk between the luminaire and wall. If this is the case, cross-baffles can be installed, but this cuts down on the horizontal spread of the wall-wash. A better solution is a blade running parallel to the lamp that partially blocks the view of the bright lamp.

CHALKBOARD OR WHITEBOARD LIGHTING

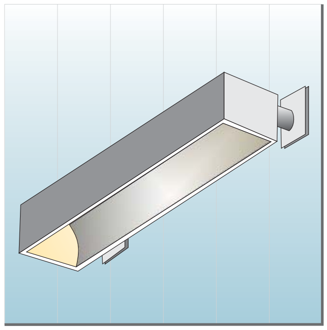


Figure 7-44 – Chalkboard or Whiteboard Luminaire

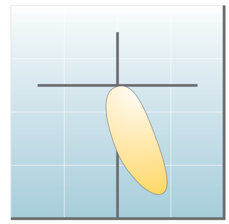


Figure 7-45 – Typical Photometric Distribution, Chalkboard/Whiteboard Luminaire

Description: It's difficult to light vertical surfaces such as chalkboards and whiteboards with wall-washers or track lights because the board's shiny finish creates a mirrorlike reflection of the luminaire. This obscures the chalk or ink markings for the viewer. A solution is to use a linear fluorescent luminaire with a narrow distribution, located near the board so that it grazes the surface.

Lamping: Use T-8 or T-5 lamps for superior optical control. See section 6.5.

Materials: The lensed or reflector optics should produce maximum intensity between 5 and 25 degrees from nadir, in the plane perpendicular to the board.

Operation and Maintenance: Some chalkboard luminaires are cumbersome to relamp because of tight lenses. Verify ease of relamping.

Efficiency: Luminaire efficiencies of 50% or greater are available.

Design and Control Considerations: Consider switching the chalkboard lighting separately from the ambient lighting in the room so that it may be switched on or off to attract attention (or not) to the board. See chapter 8 for more about controls.

RECESSED ROUND WALL-WASHERS

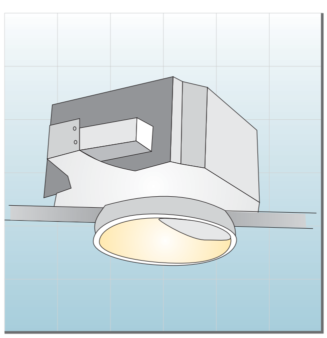


Figure 7-46 – Recessed Round Wall-washers

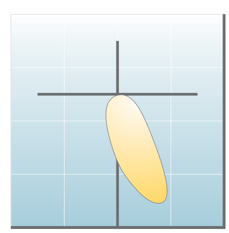


Figure 7-47 – Typical Photometric Distribution, Recessed Round Wall-washers

Description: These luminaires match recessed round downlights in appearance, but exhibit an asymmetrical throw of light.

Lamping: Advanced luminaires use compact fluorescent (section 6.5.6) or metal halide lamps (section 6.6.2).

Materials: These luminaires may incorporate a reflector or an angled lens or a combination of the two to spread the light on the wall. The lens has the advantage of spreading the lamp brightness over a larger area of the luminaire, minimizing distracting glare for the user, but also reducing efficiency.

Operation and Maintenance: Units with "cutout reflectors" are frequently installed backwards. Although not intuitively obvious, the cutout portion should be located on the side opposite the wall it is lighting.

Efficiency: Luminaire efficiency should exceed 60%.

Design and Control Considerations: The best wall-washers produce light near the top of the wall, a smooth-appearing pattern of light from the top to the bottom of the wall, and a minimum of light scalloping on the wall between luminaires.

RECESSED WALL SLOTS

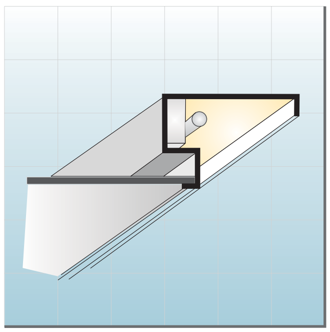


Figure 7-48 – Recessed Wall Slots

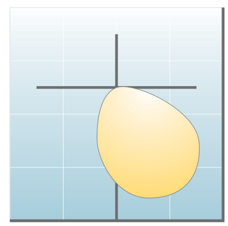


Figure 7-49 – Typical Photometric Distribution, Recessed Wall Slots

Description: The term "wall slot" is a bit of a misnomer because this type of luminaire actually creates a slot in a *ceiling*, along the length of the wall. The slot may be open, or may have a lens or baffle or louver to block the view of the fluorescent lamps.

Lamping: T-8 or T-5 fluorescent lamps are run continuously along the length of the slot, sometimes with staggered lamping to minimize socket shadows (the dark stripes that occur when lamps sockets are butted together). See section 6.5.

Materials: Small-cell plastic parabolic louvers or egg-crate louvers should be avoided because they are inefficient. Polished aluminum reflectors can be added above the lamp to direct more light to the base of the wall in order to even out the light pattern from top to bottom.

Operation and Maintenance: The effectiveness of the slot is highly dependent on the reflectance of the wall it is lighting, since that wall is doing much of the work of reflecting light into the room. Lighter color walls work much better.

Efficiency: Look for luminaire efficiencies that exceed 49%.

Design and Control Considerations: Look for good shielding of lamps from normal view. Wall slots are an effective way to help a room appear larger and brighter. However, the grazing light will accentuate flaws in the surface of the wall it is lighting.

RECESSED ACCENT LIGHTS, INCANDESCENT AND METAL HALIDE

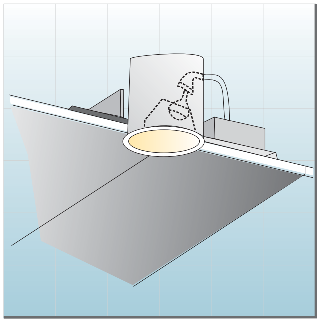


Figure 7-50 – Recessed Accent Light (MR-16)

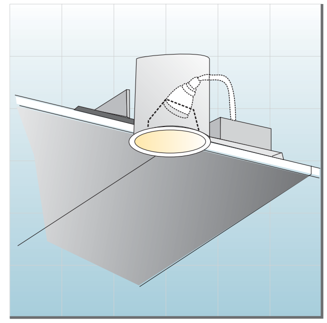


Figure 7-51 – Recessed Accent Light (MH PAR)

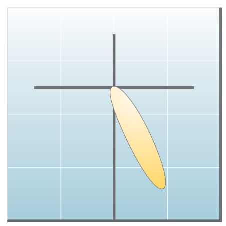


Figure 7-52 – Typical Photometric Distribution, Recessed Accent Lights

Description: Accent lights put a concentrated beam of light on an object or surface and usually use point sources such as halogen lamps or metal halide lamps. Compact fluorescent sources are usually too large for good optical control, so they don't end up being energy effective.

Lamping: In North American retail applications, the most common lamps used are MR-16 (halogen), PAR-30 (halogen and metal halide), and PAR-38 (halogen). All of these lamps have the advantage of easy relamping by individuals with a moderate amount of training. There are also metal halide accent lights that use the single- and double-ended compact metal halide lamps, but these are somewhat more complicated to maintain because there is an awkward protective glass in the luminaire that must be removed for relamping. Luminaires that utilize halogen infrared MR-16, PAR-30, and PAR-38 lamps are an improvement over conventional incandescent and halogen lamps. Whenever dimming and additional initial cost are not obstacles, consider using ceramic metal halide lamps for accent lighting. For more about halogen and metal halide sources, see sections 6.4 and 6.6.2, respectively.

Materials: Because the optics of the system are primarily contained in the lamp, many optical materials can be used successfully.

Operation and Maintenance: See Lamping.

Efficiency: Efficiencies of greater than 80% are available, although luminaire efficiency is hard to verify for these luminaires, because most of the optics are contained within the lamp itself.

Design and Control Considerations: Not all accent lights are marketed with a realistic range of adjustment. Some adjustable accent lights are catalogued as having a 45 degree aiming angle (from 0 degrees straight down, up to a 45 degree vertical angle) when most of the light from the lamp is blocked by the cone at the higher angles. Advanced products allow aiming above 30 degrees without a significant loss of light.

7.5.4 Direct ("Downward") Lighting: Track Lighting

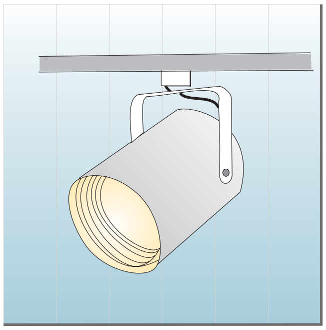


Figure 7-53 – Track Lighting (Incandescent)

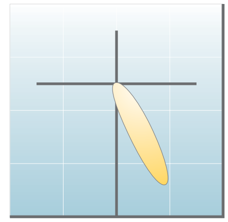


Figure 7-54 – Typical Photometric Distribution, Incandescent Track Lighting

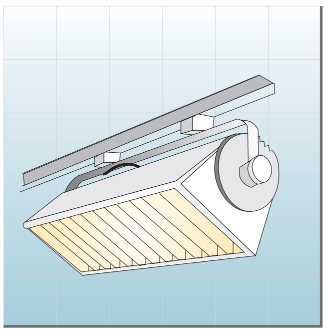


Figure 7-55 – Track Lighting (Fluorescent)

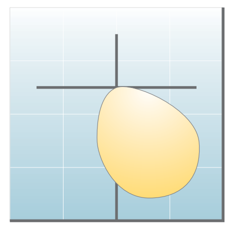


Figure 7-56 – Typical Photometric Distribution, Fluorescent Track Lighting

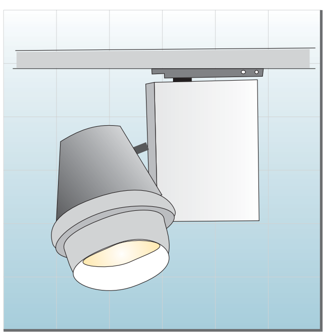


Figure 7-57 – Track Lighting (Metal Halide)

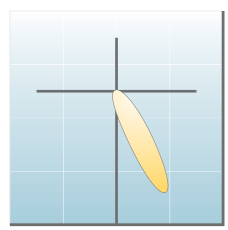


Figure 7-58 – Typical Photometric Distribution, Metal Halide Track Lighting

Description: Track lighting provides tremendous flexibility in comparison to recessed or surface-mounted luminaires, especially for ever-changing retail applications. Track lights may be selected and changed, located and relocated, aimed and re-aimed to achieve the best visual effect. Different track heads are available for accent lighting, wall-washing and downlighting. Glare control is achieved through proper aiming and lamp selection, but track head accessories such as cross-baffles, honeycomb louvers, and cube-cell louvers also control glare. Lamp selection is especially important because most accent track luminaires are just lamp holders; the lamp itself controls the beam of light.

Lamping:

- *Incandescent.* Where dimming is needed, halogen luminaires are an economical choice for spotlighting or accent-lighting applications. For the best energy efficiency, look for track heads that use these lamp shapes: MR-16, PAR-30 or PAR-38. These lamp types are available with halogen infrared technology. The MR-16 is a low-voltage lamp that offers superior beam control and wattage ranges and a very small profile, but it requires a transformer. This makes the initial cost somewhat higher than the cost for PAR-30 and PAR-38 track heads, even though the lamp cost is somewhat lower. Conversely, the PAR-30 and PAR-38 lamps are more costly to purchase, while the track head for this medium-base lamp is inexpensive. See section 6.4 for more about halogen light sources.
- *Fluorescent.* Fluorescent lamps are too large to produce concentrated beams of light. Instead, they are well suited for producing flood distributions and wall-washing. Track heads with one or two T-5 compact fluorescent lamps are less than 2 ft in length, and produce as much light as three times their wattage in halogen lamps. This reduces the number of track heads cluttering the ceiling, as well as reducing maintenance because the lamp life is longer. Specify electronic ballasts for best energy efficiency, lower weight and reduced flicker. Fluorescent lamp track heads often require baffles to reduce glare for shoppers or room occupants. See section 6.5 for more information about fluorescent light sources.
- *Metal Halide.* Metal halide lamps have improved dramatically in recent years. Ceramic arc tube lamps driven by electronic ballasts produce high CRI, 3200K light, with minimal color inconsistency and flicker. They are available in PAR-20, PAR-30, PAR-38, T-6 single-ended, and T-6 double-ended shapes, all of which have been incorporated into track light designs. Although these lamps cannot be dimmed without losing color quality, they are an excellent choice for accent lighting, wall-washing, and floodlighting track luminaires in commercial and retail applications. These lamps are very bright when viewed directly, so unless the lamp face is regressed at least 1.5 in. from the face of the track head, louvers and baffle accessories should be considered to reduce glare for room occupants and shoppers. Section 6.6.2 describes metal halide sources in detail.

Materials: Unshielded metal halide and MR-16 lamps require a tempered glass shield at the aperture of the track head to retain glass shards in the unlikely event of a lamp failure.

Operation and Maintenance: Consider ease of re-aiming and relamping when selecting track luminaires, especially if retail sales staff will do maintenance.

Efficiency: Efficiency values are seldom published by manufacturers because the efficiency varies widely according to the type of lamp and accessories used.

Design and Control Considerations: Although some track heads and track are interchangeable, most track heads are UL-rated to operate only on the same manufacturer's track. Track may be one-, two-, three- or four-circuit track. The latter is usually used only in museum or intensive retail areas. Some tracks are sturdier than others. Heavy-duty track should be used in applications where track heads will be moved or serviced frequently, such as retail and museum applications or schools. Where two or more circuits of the track are controlled separately on a dimmer, be sure to use track with separate neutrals for each circuit.

7.5.5 Direct ("Downward") Lighting: Task Lighting

Task-ambient lighting systems are an effective way to reduce energy use while allowing employees to customize the lighting for their individual work areas. The ambient lighting system provides a low-to-medium level of uniform lighting throughout an office, for example, or an industrial facility. Then separate task lighting luminaires are provided at places where more difficult visual tasks are performed: for example, at the desk in an office workstation (see Figure 7-59) or mounted to the machine in an industrial plant. Task lighting saves energy because it is mounted close to the task itself, providing high illuminances on a small area from low wattage luminaires.

Linear and compact fluorescent lamps are ideal for many task lighting applications. They are a cooler source of light than incandescent, which can be especially important given the proximity to the user. CFL task lights for industrial or maintenance applications (trouble lights) can greatly increase the comfort of the worker, as long as direct and reflected glare from the task light can be avoided.

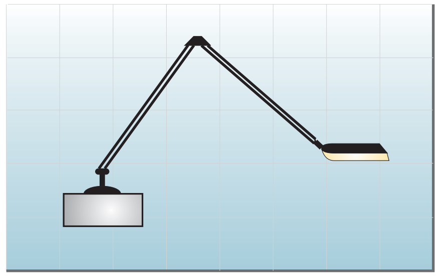


Figure 7-59 – Typical Compact Fluorescent Task Light

If the task luminaire is flexible in orientation, the user can adjust it to maximize visibility for a specific task. The task luminaire should be individually switched, so that the user can use the light, or not, according to his or her preference and need. Occupancy sensors can be built into the luminaires themselves, or installed in the workstation so that lights (and other machinery) are shut off or turned down to a minimal energy level when the user has left the area.

Task lighting systems are appropriate for many applications, including industrial, warehouse, institutional, offices and education applications. A task-ambient strategy is especially appropriate in combination with daylighting, where most ambient illumination during the day can be provided by the daylighting system. Below are some guidelines for two kinds of task lighting: fixed and furniture integrated, and portable. (Also see section 4.3.1 for general design criteria for task-ambient lighting.)

FIXED AND FURNITURE INTEGRATED

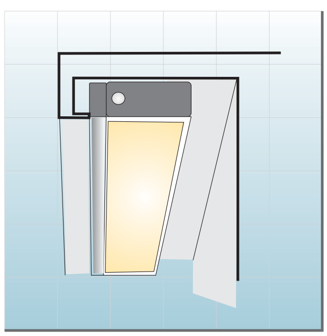


Figure 7-60 – Task Lighting, Fixed and Furniture Integrated

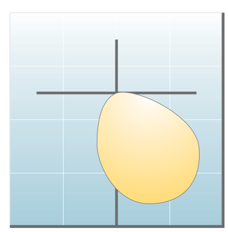


Figure 7-61 – Typical Photometric Distribution, Task Lighting, Fixed and Furniture Integrated

Description: Undercabinet task lighting is very common in offices, kitchens and classrooms.

Lamping: In advanced design, linear undercabinet lights most often use 2 ft, 3 ft or 4 ft T-8 lamps with electronic ballasts. Where the lamp is emitting more light than needed for the task, a low-ballast-factor electronic ballast (or better yet, a dimming ballast) may be specified to reduce light output and wattage. See section 6.5.3.

Materials: Bare fluorescent tubes under a cabinet should be avoided because they are so bright that they create a band of reflected glare on the work surface. There are several options to reduce these veiling reflections: a “batwing” prismatic lens in the luminaire to redirect light and improve visibility; an opaque mask that the user can reposition to block veiling reflections; a rotatable lamp sleeve printed with a gray gradient, used to block light in the direction of the viewer; or a lens that spreads the light over a large area to reduce the brightness of the reflection. Alternatively, a pair of compact fluorescent undercabinet lights mounted to each side of the user can minimize veiling glare.

Operation and Maintenance: Integral switches allow the occupant to switch on the light, or not, as needed.

Efficiency: Luminaire efficiencies should exceed 50%.

Design and Control Considerations: The designer should be sure that:

- Any direct view of the bright lamp or lens by the seated user is shielded by the luminaire itself or by a lip on the front edge of the cabinet.
- Any plastic lens elements should be clear prismatic acrylic, for best transmittance, efficiency and long-term clarity.
- For best desktop or counter illumination, the task light should be located near the front edge of the cabinet, not near the wall or partition. In order to minimize veiling reflections, often the main beam of light is aimed at the partition, rather than the front edge of the desk surface.
- Undercabinet lights can often be controlled by desk-mounted plug strips with built-in occupancy sensors. See section 8.3.

PORTABLE

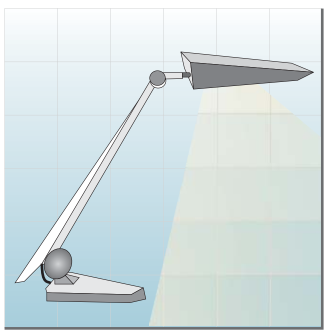


Figure 7-62 – Portable Task Lighting

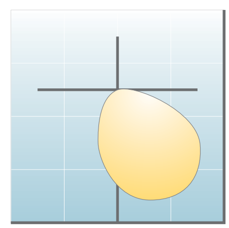


Figure 7-63 – Typical Photometric Distribution, Portable Task Lighting

Description: Portable lighting has the advantage of flexibility, and allows users great freedom in customizing their lighting according to their task or visual needs. The luminaire is best if it has an articulated head, allowing the user to set the height and tilt angle.

Lamping: Avoid halogen lamps because they are hot to the touch and are usually less efficient. Compact fluorescent lamps, either in T-4 single-, double- or triple-tube configurations, or in T-5 circline lamp configurations, offer real advantages and energy savings (see section 6.5.6).

Materials: Make certain that the luminaire has a white or metallic reflector around the lamp to improve efficiency.

Operation and Maintenance: Be aware that weighted-base task lights take up valuable “real estate” on desktops. Task lights with smaller footprints make the luminaire easier for the user to locate.

Efficiency: Efficiencies of task light products are very seldom published. More important than efficiency (as in all luminaires) is flexibility and the ability to add up to 30 to 75 footcandles on the task surface with low wattage lamps (usually 13 to 25 watts).

Design and Control Considerations: Make sure that the bare lamp is shielded from the user (and also from the user’s neighbors. Glare from task lights at neighboring desks can be more annoying than glare from one’s own task light.) Use electronic ballasts to reduce audible noise and flicker. Dimming ballasts are becoming an economically viable option.

7.5.6 Direct Lighting: Decorative Pendant Downward Light

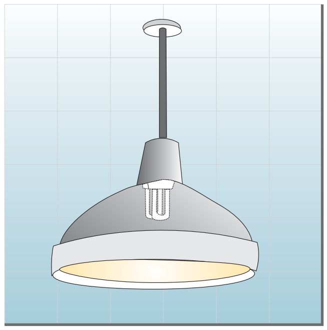


Figure 7-64 – Decorative Pendant Downward Light

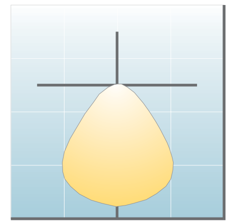


Figure 7-65 – Typical Photometric Distribution, Decorative Pendant Downward Light

Description: These luminaires are often used in retail areas over counters, in commercial lobbies over counters, or in restaurants above bars and booth tables. They are primarily decorative, but they can be useful in directing light onto a task surface.

Lamping: Wattages are usually low because they are mounted close to the viewer. If 32 watt or lower wattage compact fluorescent is used, consider using a luminaire with a diffuser or lens to reduce bare lamp glare. If incandescent lamps are needed for dimming, consider PAR-30 halogen lamps.

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladder for maintenance.

Efficiency: Overall efficiencies can exceed 86%.

Material, Design and Control Considerations: The appearance can vary widely, from “industrial” to “whimsical and contemporary” to “traditional” in brass and green glass. See Lamping for control considerations.

7.5.7 Direct (“Downward”) Lighting: Shelf Lighting

Description: Shelf lighting is used to highlight displayed or stored goods in supermarkets and other kinds of retail stores. Sometimes shelf lights are mounted inside glass cases, so they need to be small in profile to avoid obscuring the view of the products. These luminaires should be mounted at the front edge of the shelf so that light is directed toward the merchandise, and away from the view of the shopper. In the past, linear strips with a series of incandescent lamps have been used, or larger T-8 fluorescent striplights.

Lamping: The extremely small diameter (1/4 in.) T-2 fluorescent lamp is an excellent light source for advanced display luminaires. Wattages may be low because the luminaire is mounted close to the featured products. The longer lamp life (10,000 hours) and cooler operation of these lamps make this system an efficient alternative to incandescent systems. T-5 lamping can be considered for larger shelves or areas where very high illuminances are needed.

Materials: The reflector behind the lamp should be high in reflectance for best efficiency, but also designed to block the customer’s view of the very bright lamp.

Operation and Maintenance: Ballasts are often remote mounted to minimize the size of the luminaire. These shelf lights are often difficult to reach and tricky to relamp. Consider ease of access to the lamp and ballast. Specify products with heat-resistant acrylic lenses if there is any risk of hitting and breaking the lamp during normal retail operations, or risk of fading of merchandise from the small amounts of UV emitted from the fluorescent lamp.

Efficiency: 70% and greater are available.

Design and Control Considerations: Provide obvious switches or automatic control so that lamps do not remain on after shopping hours.

7.5.8 Indirect Lighting ("Uplighting")

Lighting systems are considered indirect when their light bounces off of ceilings and walls before reaching the work plane. Usually these are suspended uplights, cove uplights, freestanding uplights (torchieres) or uplight luminaires mounted to walls or furniture. It is critical for energy efficiency that the ceiling be white or very light in color.

When well designed, indirect lighting provides excellent quality ambient light that is uniform, low in direct and reflected glare, and nearly shadow-free. When computer screens are used in the space, the pattern of light created by the uplights is important. There should not be any bright stripes or light/dark striations created on the ceiling because these harsh “gradients” may be reflected in the screen. The strong stripes or patterns may also be visually distracting. For energy efficiency, indirect systems should be used in combination with task lighting to provide high task illuminances only where needed or where it is difficult for light to penetrate. In some instances, task lighting is provided more for occupant preference than as a necessity.

This section focuses on the following types of luminaires for indirect lighting:

- Suspended linear fluorescent lighting
- Decorative indirect pendants
- Wall-mounted and cove uplighting
- Portable torchiere uplights

SUSPENDED LINEAR FLUORESCENT LIGHTING

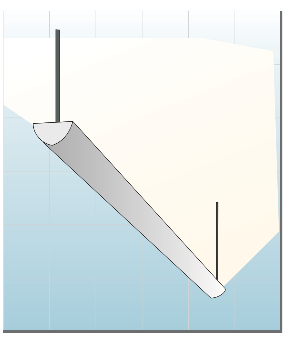


Figure 7-66 – Suspended Linear Fluorescent Luminaire

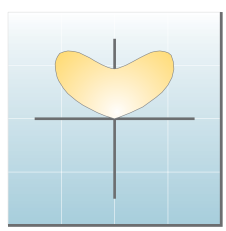


Figure 7-67 – Typ. Photometric Dist., Suspended Linear Fluorescent Luminaire (wide up)

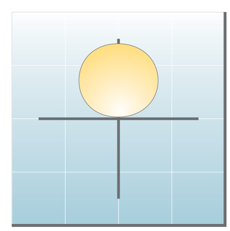


Figure 7-68 – Typ. Photometric Dist., Suspended Linear Fluorescent Luminaire (cosine up)

Description: Uplight luminaires are most efficient when they are open on the top, with no lenses or diffusers to absorb light or trap heat.

Lamping: The use of smaller T-5 and T-5 High Output (HO) linear fluorescent lamps in indirect luminaires can provide significant improvement in luminaire efficiency and optical control over T-8 lamps. T-5 full-size fluorescent lamps are 37.5% smaller in diameter than equivalent T-8 lamps and the high output version can emit up to 1.7 times the lumen output. The smaller lamp diameter and higher output lamp means that a single T-5 HO lamp can be used in place of one or two T-8 lamps, reducing the size of the luminaire. When used in conjunction with a widespread optical system, rows of luminaires can be spaced further apart, often up to 14 ft. As a result, a well-designed T-5 HO uplighting system may be more effective and no more expensive than conventional T-8 uplight systems. (See section 6.5 for a detailed discussion of linear fluorescent sources.)

Materials: Luminaire housings can be made from extruded aluminum and formed steel. Extruded aluminum products generally appear straighter, especially when used in long, continuous runs. They can be lighter in weight than steel, can be extruded in lengths greater than 8 ft, and sometimes can have suspension points spaced up to 12 ft apart. The appearance of steel housings can vary widely, according to the design and care of the manufacturer. Steel products are usually made in 8 ft maximum lengths, so the quality of the joints and alignment details are critical when these are used in runs longer than 8 ft. Twelve-foot lengths in steel are possible, but the steel must be carefully engineered so that it hangs straight. Reflectors can be made from white-painted metal, specular metal, and peened metal. The reflector design is critical in reducing the ceiling brightness directly above the lamps, and in producing a smooth distribution on the ceiling.

Operation and Maintenance: All luminaires accumulate dirt, but dirt depreciation happens more quickly in indirect luminaires. A regular cleaning schedule helps keep the indirect lighting system effective and energy-efficient.

Efficiency: Uplights with efficiencies greater than 80% are available, both with widespread and "cosine" optics. High-reflectance paints and metallic finishes in the luminaire can bring these efficiencies even higher.

Design and Control Considerations: In offices where computer screens are viewed, the uniformity of light on the ceiling is important. The IESNA recommends maximum to minimum luminance ratios of 4 to 1 or less on the ceiling in VDT-intensive spaces; and 8 to 1 up to 12 to 1 in mixed VDT and paper task offices. When luminaires are mounted close to the ceiling (usually 18 in. or closer), a widespread optical system provides more uniform lighting on the ceiling. When luminaires are further away (usually 24 in. or more), the widespread optics are less critical, and a less sophisticated luminaire (with blob-like "cosine" optics) may be used effectively.

Figure 7-67 and Figure 7-68 illustrate the photometric distributions for a widespread uplight and a "cosine" uplight, respectively.

Here are some guidelines for suspended linear fluorescent lighting:

- Use luminaires with one or two lamps in cross-section as often as possible because they are more efficient than luminaires with three or more lamps across.
- As in all fluorescent systems, use electronic ballasts for high efficiency and reduced flicker.
- Use high-reflectance, matte-finish ceilings. White-painted gypboard ceilings can be over 80% reflective. Some acoustical tiles are also available at greater than 80% reflectance, but be aware that some of these tiles have a semi-gloss finish to them. This means that at some viewing angles users may see a mirror-like reflection of the bare lamp in the ceiling.
- Dimming ballasts can provide flexibility for light levels in spaces with critical computer-screen work. Many individuals performing CAD work prefer very low illuminances, for example, but the higher illuminances still need to be provided for cleaning the office and other tasks. See section 6.5.3.

DECORATIVE INDIRECT PENDANTS

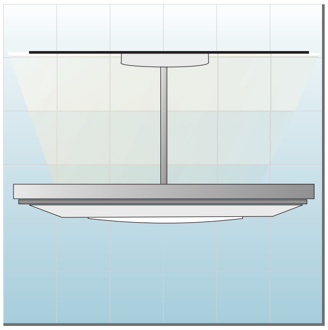


Figure 7-69 – Decorative Indirect Pendants

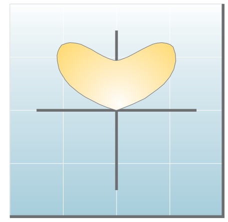


Figure 7-70 – Typical Photometric Distribution, Decorative Indirect Pendants

Description: Indirect luminaires need not be linear. Compact fluorescent lamps can now be configured into more decorative round or square pendants.

Lamping: High lumen T-5 compact fluorescent, T-5 circline fluorescent, "flat" F-shaped compact fluorescent, and even triple-tube T-4 compact fluorescent lamps are excellent options. See section 6.5.6.

Materials: See Suspended Linear Fluorescent Lighting above for additional recommendations.

Operation and Maintenance: See Suspended Linear Fluorescent Lighting above.

Efficiency: Efficiencies of 70% or higher are available.

Design and Control Considerations: These luminaires usually need to be mounted further from the ceiling (24 in. or more) in order to achieve good ceiling uniformity. Multiple lamps may be switched or dimmed to achieve multiple light levels (see section 8.2).

WALL-MOUNTED AND COVE UPLIGHTING

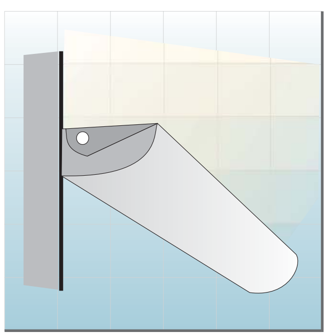


Figure 7-71 – Wall-mounted Uplighting

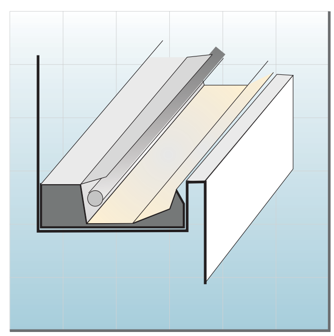


Figure 7-72 – Cove-mounted Uplighting

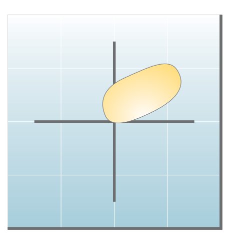


Figure 7-73 – Typical Photometric Distribution, Wall-mounted and Cove Uplighting

Description: Uplights mounted on walls can contribute to the indirect lighting from suspended luminaires, or can provide ambient lighting on its own if the space is sufficiently narrow. The luminaires may be wall-mounted linear units (such as a continuous extruded aluminum housing), individual wall-mounted units (such as a 2-ft long decorative product using compact fluorescent lamps or an 8-in. long unit using compact metal halide lamps), or the luminaires may be utilitarian fluorescent striplights or cove lights laid into an architectural shelf.

Lamping: For linear products, T-5 linear lamps permit precise asymmetrical light distributions from very small luminaires. T-8 lamps are still a good option, and T-5 compact fluorescent lamps provide very high light output per linear foot of length. For sconce products, T-5 compact fluorescent lamps or T-4 triple-tube compact fluorescent lamps are energy-efficient options, as are 35- to 100-watt T-6 ceramic arc tube metal halide lamps. In large volume retail, industrial, or commercial spaces, with 3 ft or more between uplight and ceiling, 100- to 400-watt metal halide lamps may be appropriate. See sections 6.5.2 (linear fluorescent), 6.5.6 (compact fluorescent) and 6.6.2 (metal halide).

Materials: If the luminaire is far from the ceiling (usually 2 ft or more), a simple fluorescent striplight with an asymmetrical reflector may provide adequate uniformity of light across the ceiling. If it is closer, however, the luminaire will need more sophisticated reflectors or lenses to achieve good ceiling uniformity and avoid "socket" shadows on the wall behind the luminaire.

Operation and Maintenance: Metal halide lamps should be used in commercial or retail environments where luminaires will stay illuminated all day long, since there is a 5 to 10 minute restrike time.

Efficiency: In linear products, look for luminaire efficiencies of 70% or more, and products that emit maximum candlepower between 100–130 degrees in the 90 degree plane.

Design and Control Considerations: Design recommendations for wall-mounted and cove uplighting include the following:

- The wall behind the luminaire contributes to the amount of light reaching the work plane, sometimes as much as 25%. A dark color paint or dark wood finish will reduce light levels.
- Choose luminaires with electronic ballasts. Dimming ballasts are available for compact fluorescent lamps. They are available for metal halide lamps as well, but there are a number of limitations: delayed response to the dimming signal, loss of CRI and shift in CCT as the lamp dims, and a limited dimming range.
- The light pattern on the wall and ceiling from uplight sconces will not be continuous, so make sure that the rhythm of the light patterns correspond to any patterns in the ceiling grid, wall panels or other design elements in the space. Mount sconces above eye level so that the bright lamps cannot be seen directly by occupants, and provide proper shielding so that users are not bothered by glare from the lamp or bright elements of the luminaire.
- If the luminaires are mounted below 84 in. above the floor, they should not project more than 4 in. from the wall in order to comply with the Americans with Disabilities Act (ADA).

PORTABLE TORCHIERE UPLIGHTS

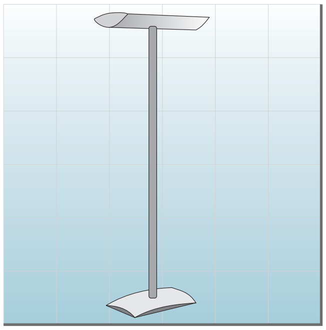


Figure 7-74 – Portable Torchiere Uplight

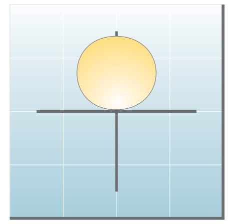


Figure 7-75 – Typical Photometric Distribution, Portable Torchiere Uplight

Description: Portable torchieres have become very common in commercial as well as residential spaces, but most torchieres have traditionally used 300- to 500-watt halogen lamps. These lamps can be a fire hazard if, for example, a combustible drape blows onto the top of the torchiere, or if the lamp is too close to the ceiling. Now that high lumen output compact fluorescent lamps are widely available, CFL torchieres should be considered in offices, lobbies and similar spaces. Metal halide torchieres have similar applications.

Lamping: Attractive and effective T-5 circline, F-lamp compact fluorescent, 2-D compact fluorescent, and T-5 twin-tube fluorescent torchieres are on the market (see section 6.5.6). Also available are 68-watt “DC” metal halide and 70-watt double-ended metal halide torchieres. As a rule of thumb, 1 watt of fluorescent or metal halide is equivalent to 3–4 watts of halogen in light output. Torchieres with compact fluorescent lamps should use 55 watts or more. In offices, freestanding torchieres are available with up to 160 watts of compact fluorescent lamping.

Materials: Reflector materials should be high-reflectance paint or hammered (“peened”) metal, or another finish that helps smooth out the pattern of light produced. This minimizes distracting stripes or rings that could be cast on the ceiling.

Operation and Maintenance: Regular cleaning of torchieres keeps light output high.

Efficiency: Look for efficiencies greater than 68%.

Design and Control Considerations: Ideally, torchieres should be equipped either with 2- or 3-level switching or a dimming ballast, in order to allow the user to customize his or her lighted environment and to save energy (see chapter 8). When there is a glass or acrylic detail to the torchiere, check that lamps, sockets and ballasts don’t create distracting bright spots or ugly shadows on the glass.

7.5.9 Direct-Indirect ("Upward-Downward") Lighting

Direct-indirect lighting systems offer many advantages in offices, classrooms and similar spaces. The uplight (indirect) portion provides bounced lighting that is good for uniform ambient light and for softening shadows on faces, and when properly designed, also minimizes reflected glare. The downlight (direct) portion adds highlights to desktops, objects and faces, helping the space appear clear and creating visual interest.

A direct-indirect luminaire can also be very energy efficient. The relative amount of uplight to downlight will vary widely with the application, but ratios of 85%/15%, 75%/25%, 65%/35% and 55%/45% are very common. The upward portion is open, allowing for high efficiency, and the downward aperture will have a lens, louver, baffle, perforations, or other opening to allow light through while controlling the direct view of the lamp. Adequate glare control of the downlight component is an essential criterion in the selection of direct-indirect luminaires in order to minimize uncomfortable overhead glare for users.

The following types of luminaires for direct-indirect lighting are covered here:

OPEN HID "HIGH-BAY"—GLASS OR PLASTIC REFLECTOR

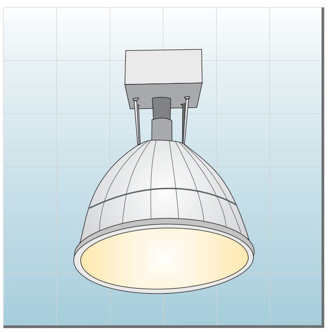


Figure 7-76 – Open HID High-bay Luminaire, Glass or Plastic Reflector

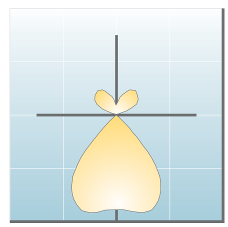


Figure 7-77 – Typ. Photometric Dist., Open HID High-bay Luminaire, Glass or Plastic Reflector

Description: These luminaires are very similar to the metal reflector "high-bay" units except that they use a glass or acrylic reflector to redirect light from the lamp downward. They also allow a small percentage of light to be emitted upward through the reflector.

Lamping: Use coated lamps to reduce the glare of the bare lamp. If using metal halide lamps, consider pulse-start lamps for higher efficiency, longer life, and better lumen maintenance. See section 6.6.

Materials: The reflector material is very important. Glass is a very durable material that remains clear over life, although it can be heavy and more expensive than plastic options. Acrylic reflectors should be UV-stabilized but may yellow or become less transmissive over a period of years. Polycarbonate reflectors are tougher than acrylic, but will yellow and become brittle much more quickly than acrylic, especially when used with metal halide or mercury lamps.

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladders for maintenance.

Efficiency: Overall efficiencies can exceed 86%.

Design and Control Considerations: These luminaires may produce up to 25% uplight, with excellent downward control of light. See recommendations for coated lamps and "hi-lo" systems in the subsection, Open HID "High-Bay"—Metal Reflector, above.

SUSPENDED DIRECT-INDIRECT LINEAR FLUORESCENT LIGHTING

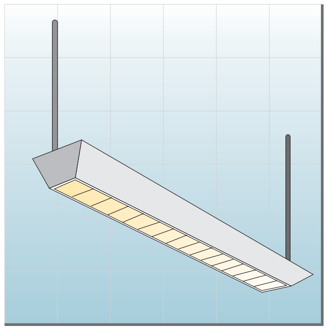


Figure 7-78 – Suspended Direct-Indirect Fluorescent Luminaire (mostly up)

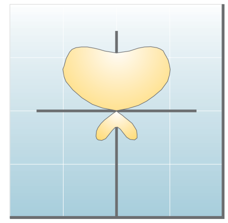


Figure 7-79 – Typical Photometric Distribution, Suspended Direct-Indirect Fluor. (mostly up)

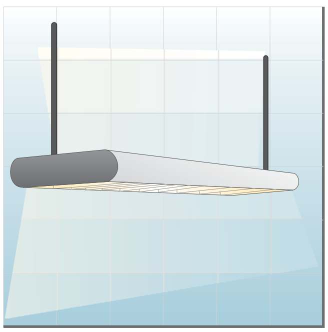


Figure 7-80 – Suspended Direct-Indirect Fluorescent Luminaire (mostly down)

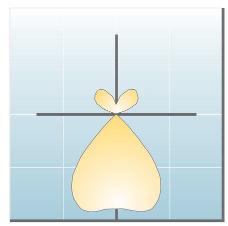


Figure 7-81 – Typical Photometric Distribution, Suspended Direct-Indirect Fluor. (mostly down)

Description: Suspended linear fluorescent direct-indirect luminaires have a lot to offer offices, classrooms, lobbies, and similar spaces. They can produce high illuminances with excellent glare control, and the combination of direct and indirect lighting often lights faces pleasantly. They can be hung as individual units, or continuous rows. With a wider spread of uplight, the rows may be spaced farther apart and still produce uniform illuminances on the work plane. The percentages of uplight and downlight vary. Offices usually use more uplight; retail spaces usually use more downlight.

Lamping: One, two, or three T-8 fluorescent lamps combined with small-profile ballasts allow luminaires to be smaller in profile. One T-5 HO linear lamp or high-lumen twin-tube compact fluorescent lamp can be used, but the lamp is so bright that there needs to be very good shielding or lensing in the downward aperture to prevent users from sensing overhead glare from the luminaire. See sections 6.5.2 (linear fluorescent) and 6.5.6 (compact fluorescent).

Materials: If baffles or louvers are specified, they should be clear or semi-specular aluminum blades for best efficiency, or painted white. Uplight reflectors may use polished and/or matte finish materials with reflectances greater than 90%. Consider wave guide luminaires to combine a soft translucent glowing material with excellent brightness control.

Operation and Maintenance: Consider electronic dimming ballasts to reduce light output when daylight is available or lower illuminance values are desired.

Efficiency: Look for efficiencies of at least 80%.

Design and Control Considerations: Keep ceilings high in reflectance, and keep luminaires mounted at least 18 in. from the ceiling unless the luminaire has a widespread uplight distribution. The guidelines for parabolic louver downlighting described above apply to the downlighting side of the up/down luminaire.

- New three-lamp, T-8 fluorescent, direct-indirect luminaires are available with on-board capability for personal dimming, and daylight and occupancy-sensing controls. These luminaires, designed for mounting into T-bar grid ceilings, provide the opportunity to control the luminaires individually from a personal computer and as a group from an energy management system. The luminaires are equipped with data network cable connectors that interface with the user's local area network. Personal controls allow the user to control the amount of downlight in their task area while maintaining uniform uplight in the general office area. Chapter 8 covers controls in detail.

DECORATIVE DIRECT-INDIRECT PENDANTS

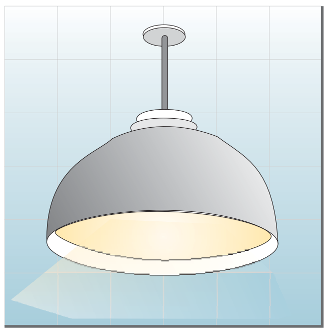


Figure 7-82 – Decorative Direct-Indirect Pendant

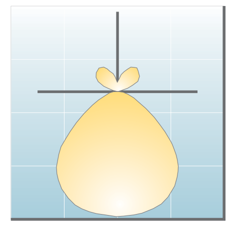


Figure 7-83 – Typical Photometric Distribution, Decorative Direct-Indirect Pendant

Description: Lighting designers are no longer limited to using incandescent lamps in decorative chandeliers and pendants. Compact fluorescent lamps can easily be used in beautiful glass, acrylic, simulated parchment and rice paper pendants.

Lamping: Fluorescent pendants may use one or more lamps ranging from 32-watt triple-tube to 55-watt T-5 twin-tube (section 6.5.6). Metal halide pendants usually use between 100-watt E-17 and 400-watt BT-37 lamps (section 6.6.2).

Materials: Use luminaires with high-reflectance reflector materials to achieve high efficiencies and a widespread distribution of light upward, maximizing luminous intensity between 100 to 135 degrees. As in all luminaires, these materials need to be easily cleaned without damaging the reflection properties, because uplight luminaire are more susceptible to collecting dust and airborne debris.

Superior luminaires are designed so that the lamps, sockets and ballasts don't create hot spots or shadows on the surface of the luminous material. The bowl or pendant is usually open on the top, and the light distribution is primarily upward.

Operation and Maintenance: For aesthetic reasons, look for luminaires that will not show insects or other debris pooled at the bottom of an acrylic or glass bowl.

Efficiency: 75% or greater.

Design and Control Considerations: Decorative pendants can be used for ambient lighting in offices, lobbies, cafeterias, seminar rooms and other spaces. Many luminaires may use up to nine compact fluorescent lamps. Specify dimming ballasts or put alternate ballasts on alternate switching circuits for multilevel switching capability. See chapter 8.

There are some very effective metal halide prismatic glass pendants that produce up- and downlight. The glass encloses the lamp so that no direct view of the lamp is possible. These may have a turn-of-the-century industrial appearance, or a contemporary geometric shape. The glass prisms effectively break up the brightness of the lamp so that in many cases it may be used in retail, classroom, and even office applications without excessive direct or reflected glare. Look for a widespread light distribution upward, a batwing distribution downward, and limited intensity between 60 and 90 degrees (usually 10% or less of the maximum intensity).

Often a pendant will be used for decorative effect only, with other room lighting providing the functional lighting in the space. In this case, reduce the watts used in the pendant luminaire to the minimum needed to produce the necessary glow or sparkle. Use long-life compact fluorescent lamps to minimize needed maintenance. Or if incandescent lamps must be used for aesthetic reasons, dim the lamps to a level that will extend their lamp life.

OPEN FLUORESCENT

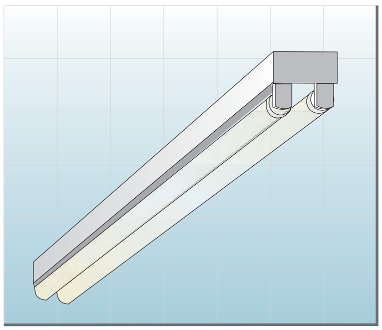


Figure 7-84 – Open Fluorescent Luminaire, Striplight

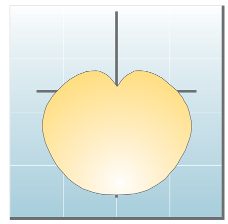


Figure 7-85 – Typical Photometric Distribution, Open Fluorescent Striplight

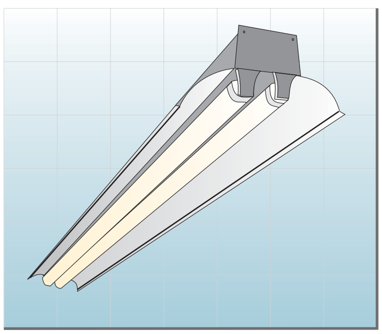


Figure 7-86 – Open Fluorescent Luminaire, Refl. Industrial

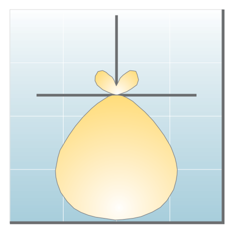


Figure 7-87 – Typical Photometric Distribution, Open Fluorescent, Refl. Industrial

Description: Open direct-indirect systems do not employ any downward shielding, so lamps are exposed to view. These systems include surface- and pendant-mounted strip fluorescent luminaires and suspended open industrial and commercial luminaires. Unless equipped with reflectors, these luminaires radiate light in all directions (see Figure 7-84 and Figure 7-86).

Lamping: 4 ft and 8 ft T-8 lamps are efficient, economical, long-life choices. See section 6.5.

Materials: High-reflectance white paint (minimum 88%) improves efficiency.

Operation and Maintenance: Slots cut into reflectors used in open fluorescent luminaires promote air movement that keeps the reflector clean of dust particles.

Efficiency: Luminaire efficiency should exceed 83%.

Design and Control Considerations: Open direct-indirect lighting systems are often very efficient, with high CU factors, but they may cause visual discomfort and disability glare. This is acceptable in many warehouse or industrial applications where luminaires are well above the heads of workers and out of the field of view.

- Electronic ballasts are a wise choice for all fluorescent luminaires. They have special safety application in industrial spaces, because the reduced flicker will not cause a strobe effect with moving machinery. See section 6.5.3.
- Reflectored luminaires produce 10–20% uplight through slots in their reflectors. This can be very beneficial because it adds light to the ceiling, reducing the perceived glare of the luminaire and contributing bounced light that helps reduce shadows cast by the luminaires.

Fluorescent industrial luminaires can easily be switched off by occupancy sensors or photosensors when the area (or warehouse aisle) is not in use, or when there is daylight available from skylights. For more about controls, see chapter **8**.

LENSED HID "LOW-BAY" LUMINAIRE

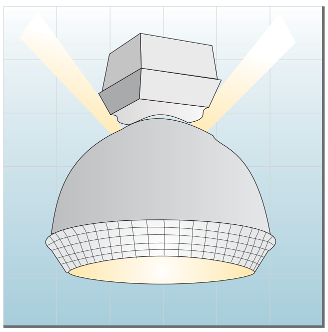


Figure 7-88 – Lensed HID "Low-bay" Luminaire

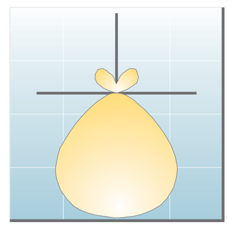


Figure 7-89 – Typical Photometric Distribution, Lensed HID "Low-bay" Luminaire

Description: These pendant, mostly downward luminaires have a metal reflector or acrylic refractor behind the lamp, and a dropped prismatic lens below the lamp. They have a widespread light distribution and are usually mounted at heights of 12 to 18 ft above the floor in industrial spaces, warehouses, sports facilities, or high-ceiling retail spaces.

Lamping: Common lamps are 100- to 400-watt metal halide or high-pressure sodium. If any color-critical work is performed, such as electrical wiring or identifying labels by color, it is wise to use MH because its color-rendering properties are superior to those of HPS. Use coated lamps to reduce flicker from clear MH lamps. If using MH lamps, consider pulse-start lamps for higher efficiency, longer life, and better lumen maintenance. Refer to section 6.6 for information about MH and HPS sources.

Materials: Reflectors are usually spun aluminum and may be polished or painted white on the interior. The dropped lens is usually acrylic or polycarbonate prismatic. Acrylic will remain clear longer than polycarbonate, especially when used with MH lamps. Polycarbonate is more vandal resistant than metal halide when the lens is new.

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladder for maintenance.

Efficiency: 75% or greater.

Design and Control Considerations: Low-bay luminaires have a wide distribution (SC >1.7), which provides better work plane uniformity at low mounting heights. However, this can also contribute to the luminaire's appearing glaring. A light reflectance ceiling combined with some uplighting can help reduce the perceived glare from the luminaire.

Look for systems that "dim" the metal halide or high-pressure sodium lamps when the space is unoccupied. Also called a "hi-lo" system, this system warms the lamp for several minutes when switched on at the beginning of the shift. Once the lamp is stabilized, the ballast drops the light output of the lamp to 25–50% if no occupancy is detected in the area. The light output idles at the low level until occupancy is detected, and the light output is brought to 100% output within seconds. (For more about hi-lo systems, see sections 6.6.6 and 8.1.3).

This system can also be used in conjunction with a photosensor in a skylit space, for example. It dims the lamps if there is daylight detected. The color rendering of the metal halide lamp drops considerably when idling at the low level, but this is seldom a problem if no one is there to see it, or if there is plentiful daylight to compensate.

LENSED COMPACT FLUORESCENT "LOW-BAY" LUMINAIRE

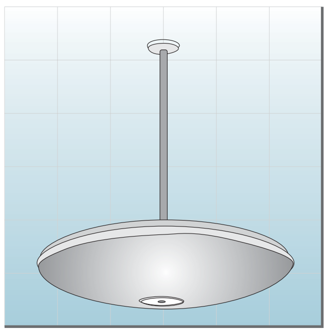


Figure 7-90 – Lensed CF "Low-bay" Luminaire

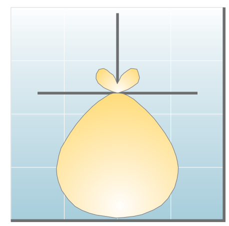


Figure 7-91 – Typical Photometric Distribution, Lensed CF "Low-bay" Luminaire

Description: These luminaires have a similar performance to HID "low-bay" luminaires, but use compact fluorescent lamps instead. They are typically used in warehouse, industrial, retail, and sports applications.

Lamping: Compact fluorescent lamps range from 26-watt "quad" lamps to 55-watt high-lumen long twin-tube lamps. Each luminaire houses up to eight lamps. While compact fluorescent lamps are lower in initial efficacy when compared to metal halide, maintained efficacy is higher, and color and color rendering are superior and consistent over life to both high-pressure sodium and metal halide. Horizontal lamps may be tilted slightly for best light output. CFLs are discussed in section 6.5.6.

Materials: Acrylic prismatic lenses should be designed for convection currents or heat sinking to minimize heat buildup around the lamps. (See section 6.5.6 for information on the relationship between ambient temperature and fluorescent lamp output.)

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladder for maintenance. There is an increased lamp replacement labor cost for fluorescent "low-bay" luminaires because there are many more lamps used when compared to HID. However, longer lamp life and energy savings may compensate for this.

Efficiency: Luminaires with efficiencies greater than 82% are available.

Design and Control Considerations: An advantage of using compact fluorescent luminaires compared to HID luminaires is that CFLs restrike instantly. Half or more of the lamps can be switched off when there is plentiful daylight available or when the space is unoccupied, and can be instantly switched back on when daylight disappears or when occupants return. Dimming ballasts are also an option. Refer to chapter 8 for a thorough discussion of controls.

WALL SCONCES—FUNCTIONAL AND DECORATIVE

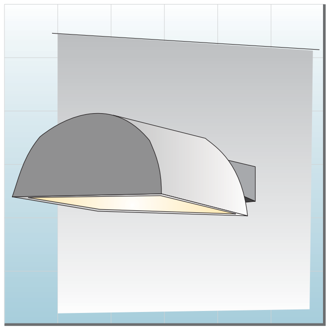


Figure 7-92 – Functional Wall Sconce

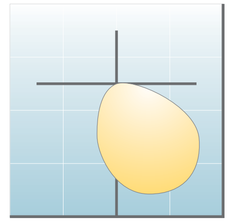


Figure 7-93 – Typical Photometric Distribution, Functional Wall Sconce

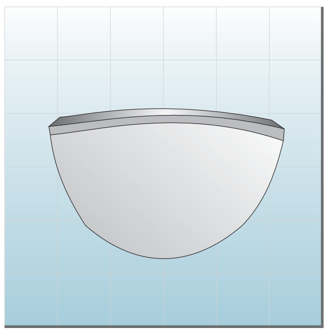


Figure 7-94 – Decorative Wall Sconce

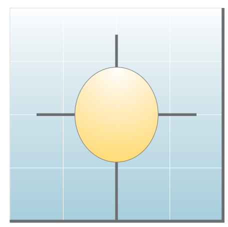


Figure 7-95 – Typical Photometric Distribution, Decorative Wall Sconce

Description: Wall sconces can be an aesthetically pleasing way to light corridors, lobbies, conference spaces, waiting rooms, offices, building facades, and other spaces. These are well-suited to the new generation of compact fluorescent lamps, and can even be dimmable when specified with compatible electronic dimming ballasts and controls. Sconces come in a wide range of styles and materials, and can provide lighting for the visual tasks, or be a low-wattage whimsical decoration for a space where other luminaires provide the functional light. Incandescent sconces should only be used where the appearance of the lamp is absolutely essential to the design aesthetic. Many sconces are available with metal halide or high-pressure sodium lamping, but are usually larger in size.

Lamping: Compact fluorescent sconces may have one or more lamps ranging from 13-watt quad tube lamps up to 55-watt T-5 twin-tube lamps (see section 6.5.6). Metal halide and HPS sconces usually use lamps that range between 35-watt and 175-watt, in T-6 up to E-17 shapes (see section 6.6). Interior sconces should use electronic ballasts for energy efficiency and reduced flicker. Sconces come in all shapes and sizes to accommodate all shapes and sizes of lamps.

Materials: Use luminaires with high-reflectance reflector materials to achieve high efficiencies. Baffles, diffusers, lenses, and louvers may be used to minimize glare for the user. As in all luminaires, these materials need to be easily cleanable without damaging the reflection properties. This is especially true if the sconces emit uplight because uplight luminaire are more susceptible to collecting dust and airborne debris.

Operation and Maintenance: For aesthetic and efficiency reasons, look for luminaires that will not show insects or other debris pooled at the bottom of an acrylic or glass bowl. Exterior sconces must be rated for wet or damp location use, as appropriate, in the orientation in which they will be used.

Efficiency: Functional interior wall sconces may have efficiencies as low as 60% if they control light distribution carefully. Decorative sconces can exceed 60% efficiency, but lower efficiencies are acceptable if low wattage lamps are used and the purpose is purely decorative. Look for outdoor sconces that exceed 50% efficiency but still control glare and distribution of light.

Design and Control Considerations: The Americans with Disabilities Act (ADA) limits the distance wall sconces can project from the wall to 4 in., when the luminaire is located below a height of 80 in. Superior wall sconces are designed so that the lamps, sockets and ballasts don't create hotspots, uneven light patterns, or shadows on the surface of any luminous materials. Sconces may provide brightness that adds to the visual interest or sparkle in a space, but can be glaring if bare lamps or bright lenses are visible, or if the lamp wattage is too high. To save energy and provide multiple light levels, consider dimming ballasts for CF lamps or alternate lamp switching in multiple-lamp sconces.

SURFACE-MOUNTED FLUORESCENT "WRAPAROUNDS"

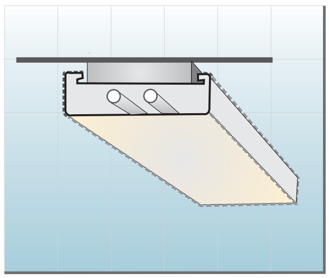


Figure 7-96 – Surface-mounted Fluorescent "Wraparound"

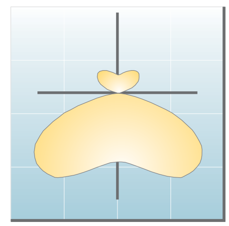


Figure 7-97 – Typical Photometric Distribution, Surface-mounted Fluorescent "Wraparound"

Description: This economy luminaire is usually mounted to the ceiling. Its sheet metal chassis contains the lamps, ballasts and lamp holders; a U-shaped "wraparound" prismatic lens hangs from the chassis edges. It produces mostly downward light, but the sides of the U-shaped lens also direct some light horizontally and upward. Almost all wraparounds are 4 ft long.

Lamping: 1, 2, 3 and 4 lamps are available in luminaires that range from 8 in. to 24 in. wide. Use no more than three T-8 lamps per luminaire, in order to minimize trapped heat that reduces lamp output. See section 6.5.

Materials: High reflectance white paint on the reflector surfaces improves efficiency. Reflectances of 0.92 or greater are possible. Use 100% acrylic prismatic lenses for long-term clarity, and lenses that obscure the lamp images, so that lamp "stripes" are not noticeable through the lens. Wraparound lenses with sides shallower than 4 in. usually have more obvious lamp images. Lens transmittance should exceed 85%.

Operation and Maintenance: Inexpensive wraparounds have open gaps at the ends of the luminaire, allowing dust and insects to get in easily. Better quality wraparound lenses may snap into the housing, reducing gaps on the ends of the luminaire.

Efficiency: Luminaire efficiencies greater than 80% are possible for two-lamp units, slightly lower for 3-lamp units.

Design and Control Considerations: When wraparounds are mounted end-to-end in continuous rows, tandem wiring of lamps will permit separate row switching. Wraparounds are suitable for closets, storage areas, corridors, some kitchens, light industrial spaces, etc. They spread light widely and produce high vertical illuminance on walls and shelving, for example, but may cause discomfort glare or computer screen glare.

WALL-MOUNTED VALANCES

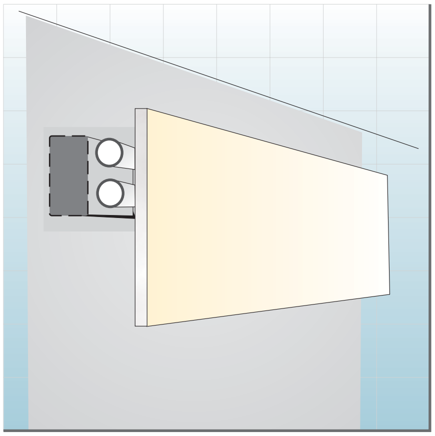


Figure 7-98 – Wall-mounted Valance

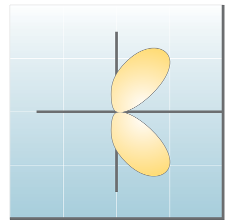


Figure 7-99 – Typical Photometric Distribution, Wall-mounted Valance

Description: Valance luminaires can be built on-site with a fluorescent striplight mounted against the wall with a 6 in. to 8 in. fascia mounted in front of it. Or, the luminaire may be purchased as a complete unit. The fascia blocks the view of the bare lamps and directs light upward and downward from the lamps. The fascia may be straight or curved, opaque, translucent or perforated metal. The fascia can be mounted to direct light mostly upward, mostly downward, or equally up and down. This type of luminaire is most often used in private offices, classrooms, conference rooms, etc. as the primary luminaire; but can be used in many other spaces to increase wall brightness and ambient light levels while controlling glare. They can be mounted as individual units, or continuous rows.

Lamping: One or two T-5HO or T-8 fluorescent lamps in cross-section are most common; combined with small-profile ballasts, these allow luminaires to be smaller in profile. See section 6.5.

Materials: The fascia may be made of a wide variety of wood or aluminum or steel materials. If continuous runs of luminaires are planned, check the details for butting fascias together, as well as how the luminaire will look when viewed end-on. For best efficiency it is very important that the fascia be painted high-reflectance white on the side facing the lamps.

Operation and Maintenance: This luminaire remains fairly clean over time because there are few horizontal surfaces to collect dust and debris.

Efficiency: 75% minimum, assuming that the wall on which the luminaire is mounted is painted high-reflectance white.

Design and Control Considerations: Keep ceilings high in reflectance, and keep luminaires mounted at least 18 in. from the ceiling. Where possible, tandem-wire lamps for separate row switching. This permits two levels of light with the same continuous pattern of light on the wall.

7.5.10 Diffuse Lighting

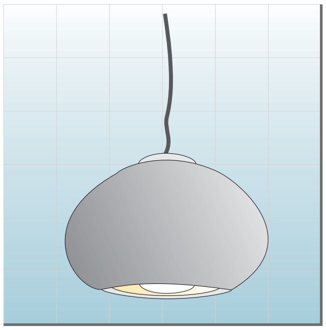


Figure 7-100 – Decorative Luminaire, Pendant

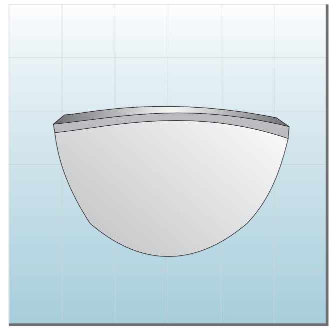


Figure 7-101 – Decorative Luminaire, Sconce

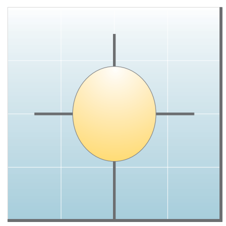


Figure 7-102 – Typical Photometric Distribution, Decorative Luminaire

Description: The category of diffuse luminaires includes decorative pendants, sconces, table lamps, and similar luminaires. A “diffuse” pattern of light can also be achieved with bare lamp luminaires, such as chandeliers or “Hollywood” light strips. Their light is emitted in all directions fairly evenly, and the luminaire can emit a pleasant glow that helps light faces.

Lamping: Diffuse luminaires can create glare, so it is a good idea to use low-wattage lamps. Use the lowest wattage compact fluorescent (section 6.5.6) or HID lamp (section 6.6) that meets the appearance goals. If the look of an incandescent filament is important to the design, use low wattage clear or frosted incandescent lamps for a low-glare glow.

Materials: Diffusers can be white or frosted clear acrylic or glass. Sand-etched or “frosted” materials are usually more transmissive and therefore more efficient than white materials.

Operation and Maintenance: Even a slight dimming of incandescent products will extend their lamp life and reduce frequency of relamping.

Efficiency: These luminaires are usually selected for appearance, not efficiency. However, sand-etched or frosted clear glass and plastic materials are more transmissive than white materials.

Design and Control Considerations: Use a minimum of these luminaires to achieve the needed decorative effect.

7.6 Outdoor Luminaires

The following types of outdoor luminaires are discussed in sections 7.6.1 through 7.6.10:

- Roadway luminaires
- Parking lot luminaires
- Luminaires for pedestrian areas
- Parking structure luminaires
- Canopy luminaires
- Wall-mounted exterior sconces and wall packs

- Landscape luminaires
- Signage luminaires
- Building facade luminaires
- Recreational sports luminaires

7.6.1 Roadway Luminaires

Roadway luminaires are intended to provide low-glare lighting on roadways to aid motorists in seeing the road, pedestrians, objects on the road and other vehicles. Electric lighting is meant to aid the motorist, not hamper the motorist. Selection of roadway luminaires should take into account horizontal and vertical light distribution, pole height, pole spacing, equipment locations and disability glare potential for the motorists. In addition, the design should minimize light trespass and pollution (for more information about light trespass and light pollution, see sections 3.2.4 and 3.2.5, respectively). The end result is enhanced nighttime visibility. Selection of roadway lighting equipment involves evaluating optical systems to achieve these goals.

Roadway luminaires are classified with respect to three criteria:

1. *Lateral light distribution.* The luminaire's transverse light distribution (perpendicular to the roadway) can be considered as types I, II, III, IV and V. Type I is long and narrow, most applicable to narrow roadways. Type III is the most common type and is used on roadways with two or more lanes. Type IV is a forward-throw luminaire with a distribution that often minimizes the light behind the pole. Type V is symmetrical in all directions. Some manufacturers have developed a classification called a type V-square to represent a distribution commonly used in parking lots.

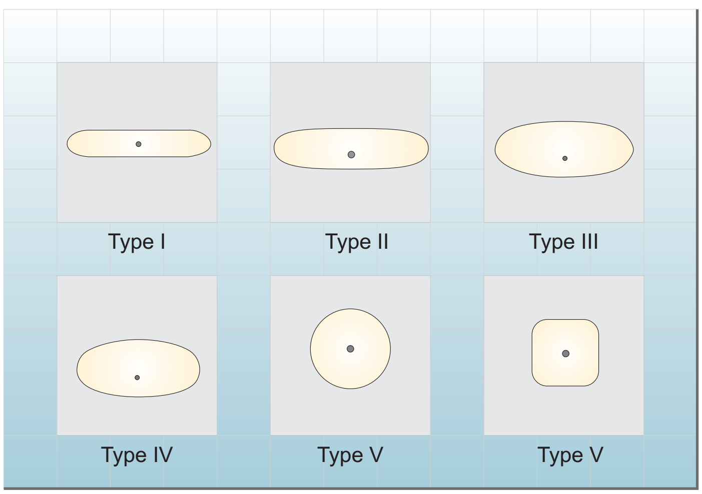


Figure 7-103 – Lateral Light Distribution Classifications for Luminaires

2. *Longitudinal light distribution.* This describes how far the light reaches along the length of the roadway (parallel to the road). The most common longitudinal distribution types for roadway applications are "long," "medium," or "short," depending on how far the light reaches along the roadway. The most common distribution is "medium" because "short" distributions result in very close spacing of poles, and "long" distributions encourage semi-cutoff that could cause disability glare for drivers. Typically, high-performance roadway luminaires fall in the "medium" distribution category.

A combination of lateral and longitudinal distributions helps the designer select particular luminaires for even light distribution with varying roadway widths and pole spacing.

3. *Cutoff.* The third criterion, cutoff, describes control of vertical light distribution above maximum intensity. The higher the angle of light, the greater the chance of disability and discomfort glare.

This is the most common classification used when determining light trespass or light pollution potential.

- A non-cutoff luminaire distributes light in any direction, or may be completely uncontrolled.
- A semi-cutoff luminaire provides some optical control, but still distributes a lot of light above the horizontal. The classification allows light intensities up to 5% of the lamp lumens to be emitted upward.
- A cutoff luminaire sends most of its light below the horizontal, yet could still have high angle light that could cause glare. Luminaire intensities above horizontal are limited to 2.5% of the lamp lumens.
- A full cutoff luminaire guarantees that its light is emitted below the horizontal. This type of distribution helps to minimize light trespass and pollution and may reduce glare.

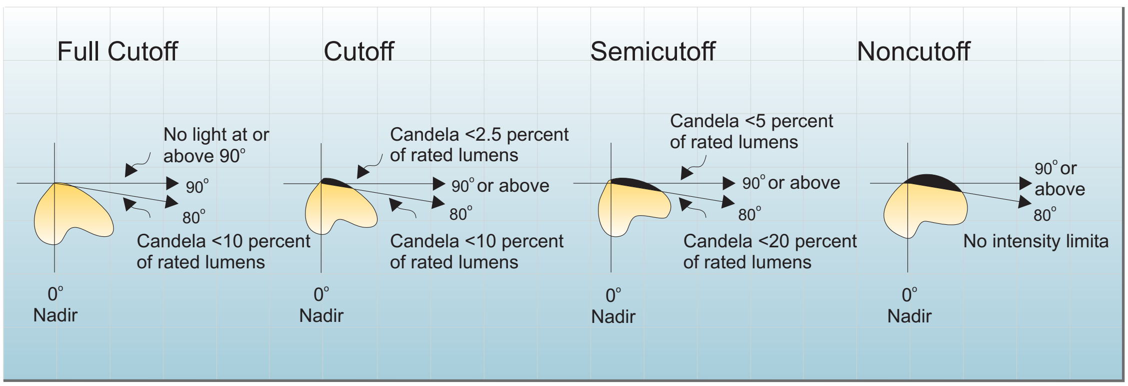


Figure 7-104 – Light Distribution of Full Cutoff, Cutoff, Semi-cutoff and Non-cutoff Luminaires
Source: http://www.nema.org/products/div2/white_papers.html

COBRA HEAD LUMINAIRES

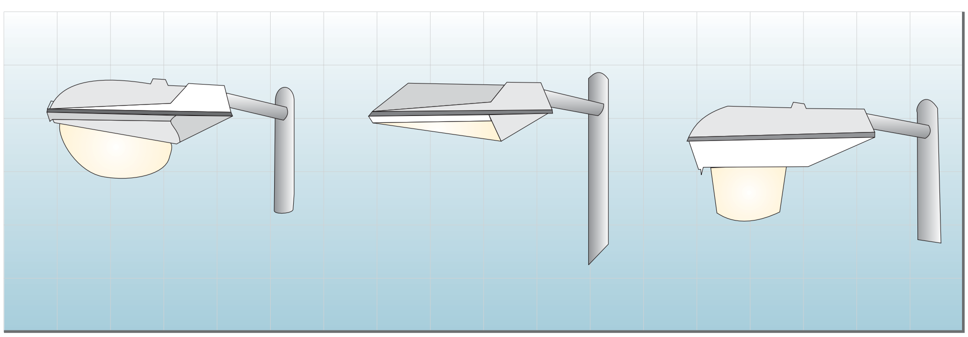


Figure 7-105 – Cobra Head Luminaire

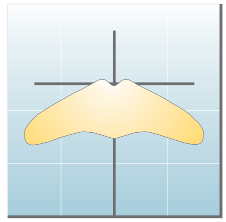


Figure 7-106 – Typical Photometric Distribution, Cobra Head Luminaire

Description: Roadway luminaires come in many different shapes and types. The most prevalent type is the “cobra head” luminaire, typically on a 6 ft davit arm. Even though these luminaires light up 90% of the nation’s roadways, they may not have the best optical systems.

Lamping: Cobra heads use metal halide (section 6.6.2) and high-pressure sodium (section 6.6.3) lamps. (Although available in mercury, mercury lamps are not recommended because of poor efficacy.)

Materials: Consider CWA (constant wattage autotransformer) ballasts instead of reactor ballasts to protect the lamp against voltage spikes.

Operation and Maintenance: Access to lamps, ballasts, and photocells should require a minimum of tools and effort, since this is usually done by maintenance people hoisted in a bucket truck blocking a lane of traffic, often in inclement weather. Luminaires should be designed to minimize the amount of insects and dirt drawn into the optical system.

Efficiency: Avoid non-cutoff luminaires. In semi-cutoff luminaires, minimum efficiencies can range between 60 and 76%, according to distribution. Similarly, minimum efficiencies in cutoff luminaires can range between 65 and 75%.

Design and Control Considerations: There are two types of cobra head basic optics: the dropped lens shape and the flat lens. The dropped lens was developed when the lighting criteria for roadway lighting was solely based on horizontal illuminance on the roadway surface. These dropped-lens cobra heads provided the best means of meeting that criteria and maximizing spacing between poles, thus minimizing the amount of equipment required. Dropped-lens cobra heads were used at the expense of disability glare in motorists’ eyes.

The flat lens cobra head was developed as a response to disability glare and other environmental concerns, such as light trespass and pollution. By replacing the dropped lens with a flat lens, the glare was reduced. However, its light distribution was no longer as wide, so spacing between poles had to decrease since design criteria were only based on horizontal illuminance.

Cobra head optical systems are very simple, with a basic formed reflector that allows lighting distributions of type II, III and IV, and short, medium and long. The dropped lens cobra heads are typically classified as semi-cutoff, while the flat lens cobra heads are classified as cutoff.

HIGH-PERFORMANCE ROADWAY LUMINAIRES

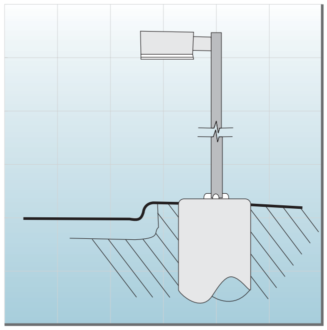


Figure 7-107 – High-performance Roadway Luminaire

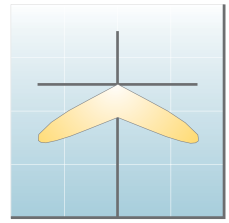


Figure 7-108 – Typical Photometric Distribution, High-performance Roadway Luminaire

Description: High-performance roadway luminaires come in many different shapes and styles. Most of them have a segmented or a specially designed formed reflector. Reflectors in these luminaires are usually larger than those in cobra heads, providing better optical control. Even though these luminaires are typically more expensive than cobra heads, fewer high performance luminaires are needed for quality design, thus saving equipment and energy costs.

The most typical high-performance roadway luminaire is the rectilinear shape commonly known as a “shoebox.” Other common shapes are semi-spherical “dome tops” or cylindrical “hockey pucks.” Since the dome tops and hockey pucks are round, their overall effective projected areas (EPA) are usually lower than that of a shoebox, requiring smaller diameter, less expensive poles.

Lamping: Lamps available for high-performance roadway luminaires are metal halide (section 6.6.2), HPS (section 6.6.3) and induction lamps (section 6.5.8). White light sources such as metal halide and induction lamps are recommended because of their increased nighttime lighting effectiveness. (The increased energy emitted in the blue-green portion of the spectrum enhances the driver’s peripheral vision under low nighttime illuminances. See discussions of peripheral vision and night conditions in sections 2.1.7 and 4.2.2.)

Materials: Reflectors may be formed or faceted aluminum. Lenses are made of impact-resistant, tempered flat glass. Look for the following features in high-performance roadway lighting:

- Rotatable optics that allow field positioning of the optical assemblies within the luminaire body to achieve the desired photometric distribution, irrespective of luminaire orientation relative to the mounting point.
- Available house-side shields to control light trespass in a predictable manner, without degrading the main portion of the luminaire photometric distribution.
- Well-machined modular components that allow field replacement of entire optical assemblies, ballasts and lens doors while maintaining integrity of enclosed unit.
- Aerodynamic profile that reduces the effective projected area (EPA) of the luminaire and consequently reduces the wind loading. This may reduce pole strength and structural base requirements.

Operation and Maintenance: Access to lamps, ballasts and photocells should require a minimum of tools and effort, since this is usually done by maintenance people hoisted in a bucket truck blocking a lane of traffic, sometimes in inclement weather. Luminaires should be designed to minimize the amount of insects and dirt drawn into the optical system.

Efficiency: Efficiencies vary according to the IESNA light distribution. They should exceed 77 to 82% for semi-cutoff luminaires, 65 to 75% for cutoff luminaires.

Design and Control Considerations: Common photometric distribution types for these luminaires are type II, III and IV. Since these luminaires typically have solid-top housings, they have cutoff and full cutoff designations, making them less likely to cause disability glare and light pollution.

In many urban areas, decorative street lighting is used to reinforce a historical appearance or help create a unified style. Decorative street lighting should have superior optical systems that are classified as type II, III or IV, preferably with a cutoff distribution. In areas where tall buildings are present and vertical light on the buildings is desirable for surface brightness, then a semi-cutoff light distribution may be appropriate. Whenever decorative luminaires are selected, the "brightness" of the luminaire should be comfortable for pedestrians to view and should minimize high-angle light that can cause disability glare for drivers.

7.6.2 Parking Lot Luminaires

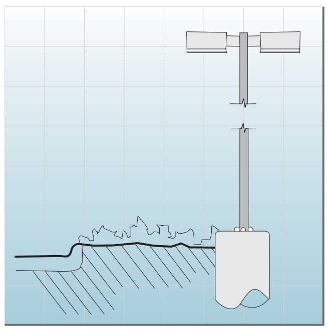


Figure 7-109 – Parking Lot Luminaire

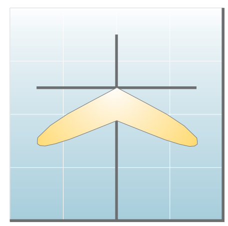


Figure 7-110 – Typical Photometric Distribution, Parking Lot Luminaire

Description: Parking lot luminaires are similar to roadway luminaires in photometric distribution characteristics and styles. There are additional distribution types that are widely used in parking lot or area lighting luminaires including type V and type V-square. Type V distributes light in a symmetrical pattern where equal amount of light goes in all horizontal directions. A type V-square distribution, widely used by manufacturers for luminaires designed specifically for parking lots, disperses light in a square pattern. When poles are mounted at the edge of the parking lot, type IV (or "forward throw") optics can be used to project light toward the center of the parking lot, while minimizing the amount delivered behind the luminaire. Full cutoff and cutoff designations are the most common types to limit light pollution and light trespass (for a discussion of light trespass and light pollution, see sections 3.2.4 and 3.2.5, respectively).

Lamping: Metal halide (section 6.6.2), HPS (section 6.6.3) and induction lamps (section 6.5.8) are the most logical options, in wattages from 70 to 400 watts. White light sources such as metal halide and induction lamps are recommended because the increased energy emitted in the blue-green portion of the spectrum enhances the driver's peripheral vision under low nighttime illuminances. (See sections 2.1.7 and 4.2.2 for more information about peripheral vision under night conditions.)

Materials: Look for the following features in parking lot lighting:

- Rotatable optics that allow field positioning of the optical assemblies within the luminaire body to achieve the desired photometric distribution, irrespective of luminaire orientation relative to the mounting point.
- Available house-side shields to control light trespass in a predictable manner, without degrading the main portion of the luminaire photometric distribution.
- Well-machined modular components that allow field replacement of entire optical assemblies, ballasts and lens doors while maintaining integrity of enclosed unit.

- Aerodynamic profile that reduces the effective projected area (EPA) of the luminaire and consequently reduces the wind loading. This may reduce pole strength and structural base requirements.

Operation and Maintenance: Look for precisely formed, sealed optical assemblies made from highly reflective materials. These should be rigidly fabricated to maximize luminaire efficiency and allow maintenance without degradation of performance. Lamp and ballast compartments should be easy to access for maintenance.

Efficiency: Luminaires should emit no more than 5% of the lamp lumens upward. Luminaire efficiencies should exceed 77% for semi-cutoff, and 65% for cutoff luminaires.

Design and Control Considerations: Parking lot lighting provides safety and security for pedestrians while walking between their vehicles and destinations, and helps motorists to see pedestrians and other vehicles. Too often security lighting is equated with high light levels. Yet low light levels with uniform light distribution, accompanied by vertical illuminance at the perimeter walls of the parking lot, help motorists and pedestrians to feel safe and see potential obstructions better than with high horizontal footcandles alone.

Even though luminaires are classified as “cutoff” type, they may still pose light trespass potential. An example of this may be a vertical lamp in a “sag” lens configuration. Even though the photometrics classify the luminaire as cutoff type, a luminaire with a high wattage lamp could easily cause undue brightness at angles near 90 degrees from the luminaire’s nadir, resulting in annoying glare to neighbors (see discussion of light trespass in section 3.2.4). “House-side shields” are metal shields that can be retrofitted in some optical systems to reduce the amount of light emitted toward a neighboring property.

Decorative luminaires with high performance optical systems may work well in parking areas, where vertical illuminance on pedestrians is very important. In all cases, the brightness of the luminaire should not cause disability glare or light trespass.

7.6.3 Luminaires for Pedestrian Areas

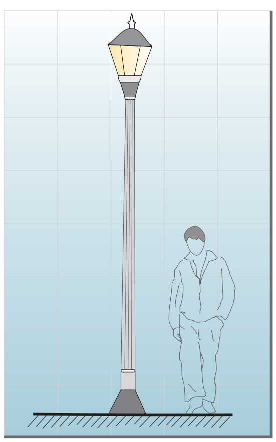


Figure 7-111 – Pedestrian Area Luminaires

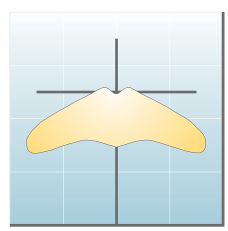


Figure 7-112 – Typical Photometric Distribution, Pedestrian Area Luminaires

Description: Pedestrian lighting located along sidewalks or pathways should be similar in appearance to roadway or parking lot lighting, but smaller in scale and brightness. High-performance luminaires described in the Roadway Luminaires section above (7.6.1) are good for lighting walking surfaces without excessive off-site glare and present minimal adverse environmental effects. Their weakness is in the limited amount of vertical illuminance that is important for pedestrian recognition.

Lamping: Consider metal halide (6.6.2), HPS (6.6.3), induction (6.5.8), and compact fluorescent (6.5.6) lamps, in wattages from 26 to 100 watts. White light sources such as metal halide, compact fluorescent, and induction lamps are recommended because the increased energy emitted in the blue-green portion of the spectrum enhances the pedestrian's peripheral vision under low nighttime illuminances. See sections 2.1.7 and 4.2.2 for more information about peripheral vision under night conditions.

Materials: Lenses may be made of glass, high-impact acrylic, or polycarbonate. Each has its application, but specifiers should be aware than polycarbonate will yellow and turn brittle within a few years of operation because it is exposed to UV from daylight and metal halide lamps. Acrylic is more stable in clarity, but less vandal resistant than polycarbonate and some heavy glass products.

Operation and Maintenance: Consider access to lamps and ballasts for ease of maintenance. Luminaires should be designed to minimize the amount of insects and dirt drawn into the optical system.

Efficiency: No more than 5% of the lamp lumens should be emitted upward. Efficiencies for semi-cutoff luminaires can exceed 60%; efficiencies for cutoff luminaire can exceed 70%.

Design and Control Considerations: Typical distribution types include type III and type V. Cutoff distributions are the most desirable since they limit light pollution and trespass. Semi-cutoff and non-cutoff should most often be limited to low wattage lamps, similar to a 26-watt compact fluorescent and below.

Decorative luminaires that have shielded or well-designed optical systems should be considered. In these cases, light is directed primarily to the path yet also lights people's faces with a comfortable brightness.

Bollard luminaires are popular in pathway lighting. Bollards are great indicator lights, but don't necessarily light people's faces, though they do a great job of lighting feet. The best use of bollards is to identify potential hazards by providing indicator lighting. Avoid using too bright of a light source in bollards as they have a glare potential. Select bollards that direct light to the ground and are low brightness in normal viewing angles.

7.6.4 Parking Structure Luminaires

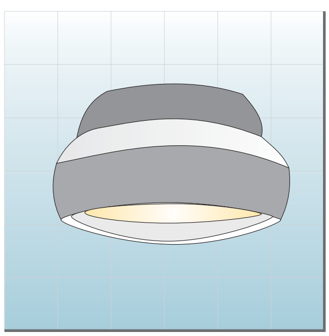


Figure 7-113 – Parking Structure Luminaire

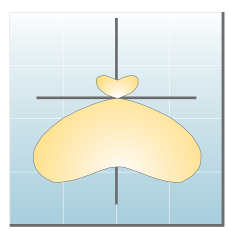


Figure 7-114 – Typical Photometric Distribution, Parking Structure Luminaire

Description: Advanced parking garage luminaires that comply with IESNA RP-20-98 recommendations for lighting parking garages are available for low-to-medium wattage metal halide and high-pressure sodium lamps. These high-performance luminaires have adjustable cutoff angles, and may be equipped with a light trespass shield and a glare guard to redirect light. They also have an uplight component to improve the interior luminous environment.

Luminaires should distribute light to the ceiling and to the floor without excessive brightness to the driver. Luminaires are classified as direct-indirect luminaires, though they are unique since the 90-degree elevation plane (or equator plane) should emit very little or no light.

Fluorescent luminaires can also do an excellent job in parking garages. The design requires a larger number of fluorescent striplights or enclosed luminaires, but the result can be more uniform, lower in glare, and lower in energy than HID systems. It is critical for the designer to consider temperature effects on fluorescent lamp starting and light output if the garage is located in a cold climate. (See section 6.2.5.)

Lamping: Recommended lamps for parking structures are metal halide (section 6.6.2) or induction lamps (6.5.8). High-pressure sodium lamps (6.6.3) are also an option, although at low light levels of HPS it is difficult to identify colors. This can have security impacts. For fluorescent systems, T-8 lamps (with low-temperature ballasts if necessary) are recommended (6.5).

Materials: Reflectors are usually formed aluminum with a shiny or "peened" finish. The dropped lens is usually acrylic or polycarbonate prismatic. Acrylic will remain clear longer than polycarbonate, especially when used with MH lamps. Polycarbonate is more vandal resistant than metal halide when the lens is new. All luminaires should be shielded with a wire guard or lens that will be resistant to breakage by automobile antennas.

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladder for maintenance.

Efficiency: Luminaire efficiency will exceed 70% for enclosed fluorescent luminaires, and 90% for open fluorescent strips. HID luminaires should exceed 80%.

Design and Control Considerations: As in any interior space, lighting the walls and ceiling is crucial in parking structures for occupant comfort. Interior walls in the parking structure should be lighted to provide wayfinding to elevators and circulation paths. Luminaires should be T-8 or T-5 sign-lighters or linear wall perimeter luminaires that will effectively wash the walls.

Drivers entering and exiting parking garages may have to visually adapt from high outdoor to low indoor light levels, or vice versa (refer to section 2.1 for more about visual adaptation). It is a good idea to have an additional set of luminaires at the entrance and exit points that switch on during daylight hours to help the driver adapt to or from the brighter outdoor illuminances.

The top open deck of a parking structure is extremely difficult to light, and especially difficult to minimize light trespass since luminaires are located so far above the ground. Pole-mounted luminaires have considerable glare potential to surrounding neighborhoods. Luminaires should be IESNA full cutoff designation with external glare shields as an option. Mount poles on the interior portion of the structure in order to minimize the light trespass impact. Use IESNA criteria for open parking lots for the lighting levels on the open deck level.

The perimeter may be lighted with recess-mounted “step” lights that are designed to put light at the front of cars parked in this outside row. Compact fluorescent lamps and 50-watt metal halide are ideal lamp selections for this perimeter lighting.

The amount of light escaping the parking structure should be minimal to reduce light trespass in surrounding neighborhoods (refer to section 3.2.4).

7.6.5 Canopy Luminaires

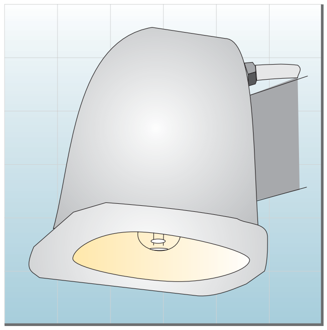


Figure 7-115 – Canopy Luminaire

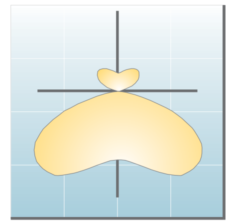


Figure 7-116 – Typical Photometric Distribution, Canopy Luminaire

Description: These luminaires are recessed into the canopies or overhangs of gas stations or outdoor drive-through areas of fast food restaurants. Uplights may be used to light the canopy if all light from the luminaires is confined to the canopy and not visible to people above or below the canopy. (Section 5.9 discusses advanced design strategies for canopy lighting.)

Lamping: Metal halide (150 watts or below; see section 6.6.2) and induction lamps (see section 6.5.8) are recommended lamps for canopy lights.

Materials: Housings should be rated for outdoor use, designed to minimize insect infiltration. Any plastics used in lenses should be resistant to UV from lamps.

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladder for maintenance.

Efficiency: Luminaire efficiency should be at least 70%.

Design and Control Considerations: Gas station canopy lighting should be completely recessed in the canopy with a flat lens, or surface-mounted with a flat lens. Canopy lights should have an IESNA full cutoff designation. Protruding lenses should be avoided, since they greatly increase disability glare and light trespass potential. Lighting levels shall not exceed levels listed in IESNA RP-33 “Lighting for Exterior Environments.”

Other canopies that are attached to buildings should provide non-glare lighting to pedestrians and motorists.

7.6.6 Wall-Mounted Sconces and Wall Packs

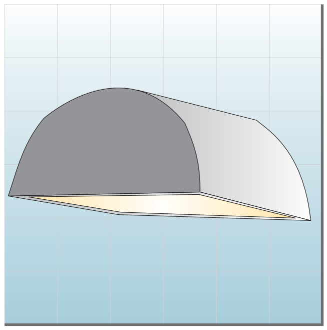


Figure 7-117 – Wall-mounted Sconce

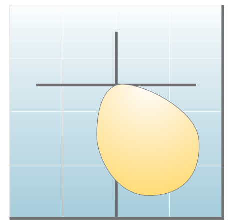


Figure 7-118 – Typical Photometric Distribution, Wall-mounted Sconce

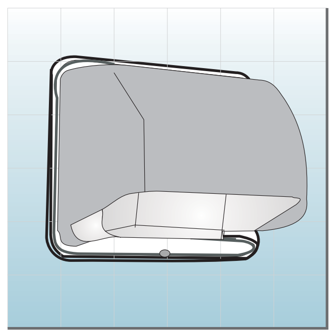


Figure 7-119 – Wall Pack

Description: Wall-mounted exterior sconces need to light the building and provide desirable surface brightness.

Lamping: Exterior wall sconces that are rated as IESNA full cutoff may use metal halide (section 6.6.2), induction (6.5.8) or compact fluorescent lamps (6.5.6). Non-cutoff luminaires used for decorative purposes and to light people's faces as they enter a building should use lower wattage compact fluorescents.

Materials: Housings should be rated for outdoor use and designed to minimize insect infiltration. Heavy prismatic glass, unaffected by UV, is often used in wall packs. Although polycarbonate is vandal resistant in its first few years of operation compared to acrylic and glass, it will turn yellow and brittle in time.

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladder for maintenance.

Efficiency: Good quality "cutoff" wall packs emit less than 2% of the lamp lumens upward, and can exceed 40% in efficiency.

Design and Control Considerations: Unshielded wall packs intended to light an area away from the building should be avoided because they are often offensively glaring to both users and neighbors (refer to section 3.2.4).

7.6.7 Landscape Luminaires

Landscape lighting involves multiple lighting techniques, from lighting trees, shrubs and other softscape features, to lighting hardscape features such as fountains, gazebos, bridges and sculptures. Landscape lighting can often provide a feeling of safety and security on pathways to supplement or replace more commercial-looking path lighting.

SOFTSCAPE LIGHTING

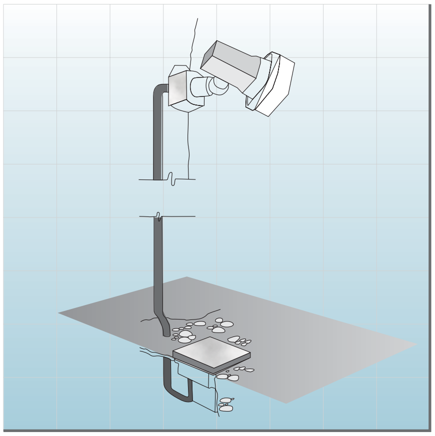


Figure 7-120 – Softscape Luminaire, Tree Downlight

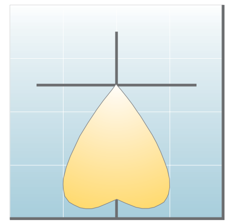


Figure 7-121 – Typical Photometric Distribution, Softscape Luminaire, Tree Downlight

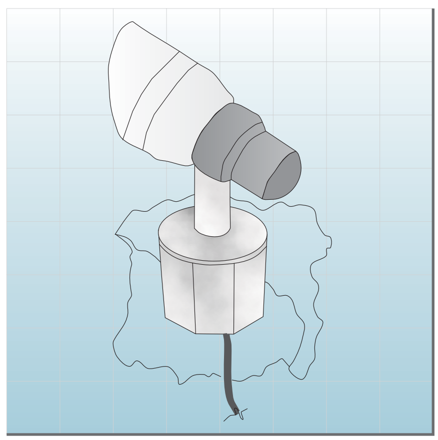


Figure 7-122 – Softscape Luminaire, MH Uplight

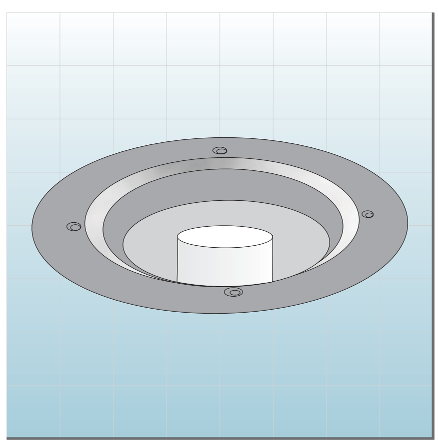


Figure 7-123 – Softscape Luminaire, Well Uplight

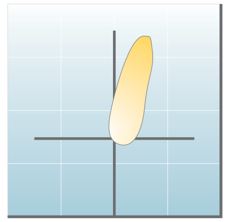


Figure 7-124 – Typical Photometric Distribution, Softscape Luminaire, Uplight

Description: These are luminaires designed to highlight trees, grass, shrubs, and gardens and their pathways and walls.

Lamping: Good color is imperative for lighting of plant materials, so halogen and metal halide lamps are most often used for accent lighting. Low-voltage MR-16 lamps provide dramatic spots and soft floods with very small housings at 50 watts or less (see section 6.4.4); metal halide PAR-20, PAR-30, PAR-38, and ED-17 lamps provide the same effects for larger scale installations, using wattages of 35 to 175 (see section 6.6.2). Compact fluorescent luminaires can be used for low-intensity floodlighting (section 6.5.6).

Materials: All non-sheltered exterior luminaires must be rated for wet locations and must be ADA compliant where applicable. Luminaires that come into contact with ground and water are susceptible to several kinds of corrosion. Some composite materials, bronze, and brass are more resistant to corrosion than steel and aluminum products.

Operation and Maintenance: Equipment should be protected from damage during typical landscape maintenance, and should avoid introducing a safety hazard such as pedestrian tripping or excessive heat. Specified equipment should consider that the plant will grow over time, so it may need periodic beam spread adjustment and height or location adjustment.

Efficiency: Look for 40% minimum for fluorescent floodlights; higher for other lamps and luminaire types.

Design and Control Considerations: If trees and shrubs are to be lighted from below, low wattage ground-mounted luminaires that are extremely well shielded with correct beam control and louvers may be used. Landscape lighted from above may involve tree-mounted low-voltage halogen luminaires designed specifically for this application. Be careful that the mounting of the luminaires does not damage the trees. Adjustable straps that allow for tree growth are available.

Consider using a time clock to turn lights off at 10 or 11 PM so that they do not contribute to light pollution after the prime hours of use.

HARDSCAPE LIGHTING

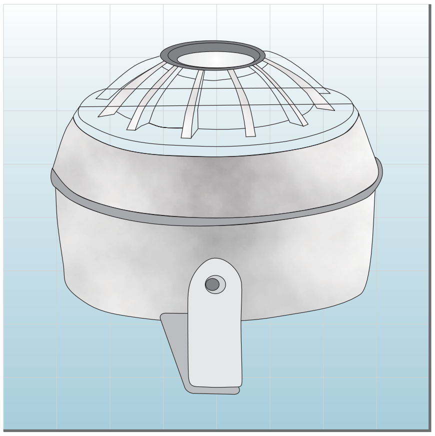


Figure 7-125 – Hardscape Luminaire, Underwater

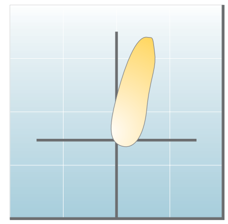


Figure 7-126 – Typical Photometric Distribution, Hardscape Luminaire, Underwater

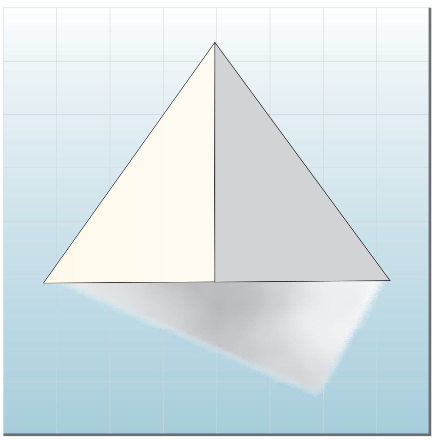


Figure 7-127 – Hardscape Luminaire, Sconce

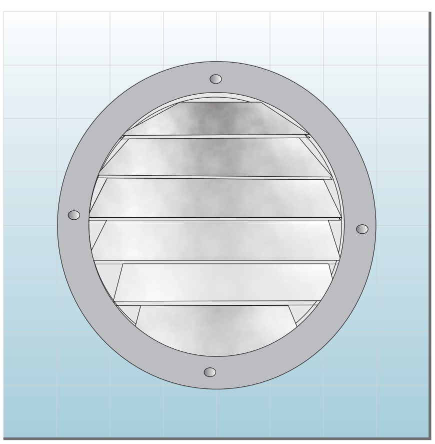


Figure 7-128 – Hardscape Luminaire, Steplight

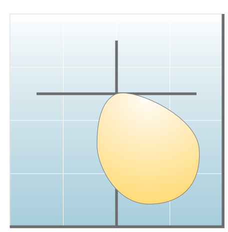


Figure 7-129 – Typical Photometric Distribution, Hardscape Luminaire, Steplight

Description: Luminaires for lighting fountains, pools, walls, bridges, gazebos, and similar features are called “hardscape lighting.”

Lamping: Lighting for gazebos, bridges and other structures may be done with a variety of types of luminaires. Recess-mounted step lights can incorporate compact fluorescents (section 6.5.6) or LED (6.7) sources. Wall sconces mounted on columns can also use compact fluorescent (6.5.6), low-wattage metal halide (6.6.2) or induction lamps (6.5.8). Occasionally, warm HPS lamps (6.6.3)are appropriate for stone or brick facades or walls, because its color is reminiscent of floodlighting done on historical buildings in Europe.

Materials: Luminaires mounted underwater in fountains or swimming pools and other water features must be rated for this application. The materials used in housings and lenses must resist corrosion and be easy and safe to maintain.

Operation and Maintenance: These luminaires must be ADA compliant if located within the mounting height restrictions.

Efficiency: The range of products is extremely broad. Efficiencies vary widely.

Design and Control Considerations: Halogen underwater luminaires require a water covering in order to keep them cool enough to operate. Some lower-wattage metal halide luminaires can operate with or without a water covering. Consider fiber optic lighting for water feature lighting, since the fiber optic cable can easily be mounted in the water without electric component or heat exposure. The metal halide or LED illuminator is located in a dry location for easy servicing.

Many times pole-mounted luminaires are used to light the pedestrian walkways, especially on bridges. Adjustable, well-shielded luminaires can light bridge abutments and other features. In all cases, light pollution and glare to motorists and pedestrians should be avoided through careful equipment selection, placement and aiming of luminaires.

Consider using a time clock to turn lights off at 10 or 11 PM so that they do not contribute to light pollution after the prime hours of use.

7.6.8 Signage Luminaires

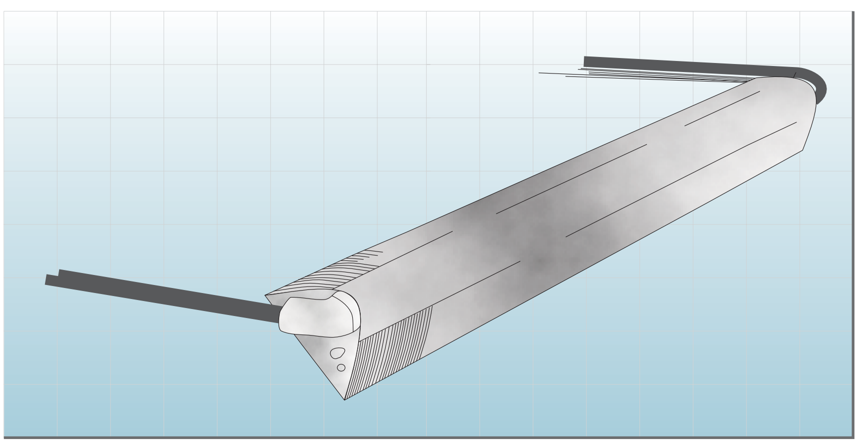


Figure 7-130 – Signage Luminaire

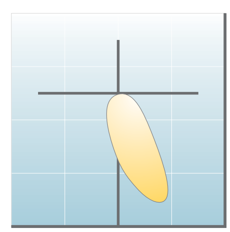


Figure 7-131 – Typical Photometric Distribution, Signage Luminaire

Description: Luminaires specifically designed for signs are equipped with asymmetric reflectors to evenly light the sign surface.

Lamping: Light sources for signage lighting may be compact fluorescent (section 6.5.6), T-8 or T-5 fluorescent (6.5.2), metal halide (6.6.2) or LED (6.7). All of these can be specified with dimming ballasts or dimmable transformers to customize and limit the amount of sign brightness.

Materials: Luminaires must be rated for outdoor use in the position they will be oriented. They should be designed to shed water and resist ice buildup.

Operation and Maintenance: Low-temperature ballasts must be specified for operating fluorescent lamps in cold weather climates.

Efficiency: Look for 70%-80% efficiency for fluorescent luminaires and a minimum of 54% for HID sign lighters.

Design and Control Considerations: Externally mounted signage luminaires should be mounted at the top of the sign. By aiming downward onto the sign, light pollution is reduced (refer to section 3.2.5).

Internally lighted signs should be lighted to a brightness that will not cause light trespass or disability glare to motorists. Lamps need to be spaced such that the surface of the sign is evenly illuminated. Most sign lights should be turned off after the prime hours of use (11 PM, for example) so that they do not contribute to light pollution or light trespass.

7.6.9 Building Facade Luminaires

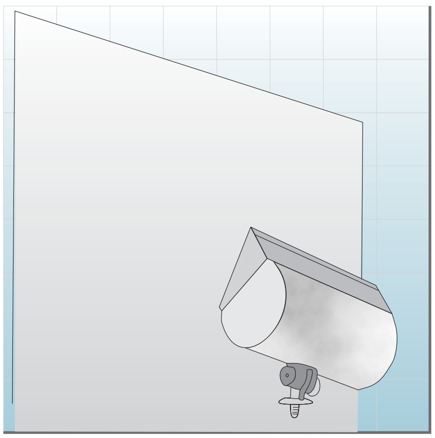


Figure 7-132 – Building Facade Luminaire, Uplight

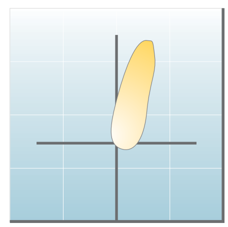


Figure 7-133 – Typical Photometric Distribution, Building Facade Luminaire, Uplight

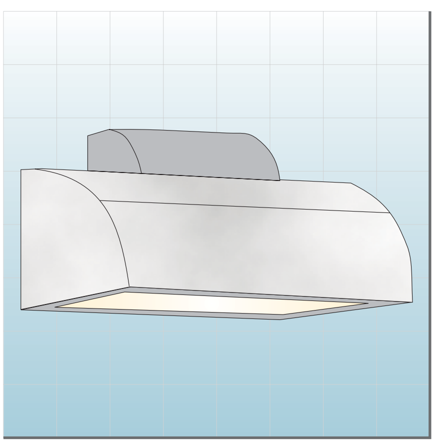


Figure 7-134 – Building Facade Luminaire, Downlight

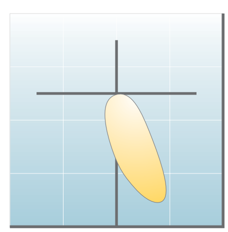


Figure 7-135 – Typical Photometric Distribution, Building Facade Luminaire, Downlight

Description: Building facades are lighted in a variety of methods and with many types of equipment. Ground- and building-mounted uplight luminaires need to control all of the light they emit so that it falls on the building facade. This can be accomplished with precise beam spread selection, louvers and shielding, and careful locations. Uplighting that contributes to light pollution is unacceptable.

Lamping: Lamping may be metal halide, PAR metal halide, high-pressure sodium, compact fluorescent, induction or LED. Refer to chapter 6 for details about these sources.

Materials: Luminaires must be rated for outdoor use in the position they will be oriented. They should be designed to shed water and resist ice buildup.

Operation and Maintenance: Low-temperature ballasts must be specified for operating fluorescent lamps in cold weather climates.

Efficiency: Products and lamps used vary greatly, so efficiencies will vary from 40 to 90%.

Design and Control Considerations: The preferred method for lighting facades is to aim luminaires downward and toward the facade. Luminaires may be recessed in soffits, or arm mounted. To reduce light pollution from reflected light from the facade, switch the lights with an astronomical time clock. This permits switching on lights at dusk, and off at a programmed time (such as 11 PM). Refer to section 3.2.5 for more strategies to control light pollution.

7.6.10 Recreational Sports Luminaires

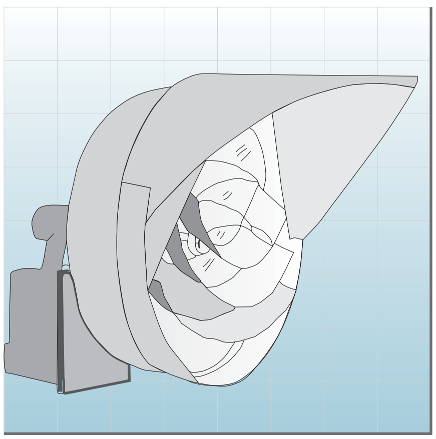


Figure 7-136 – Recreational Sports Luminaire

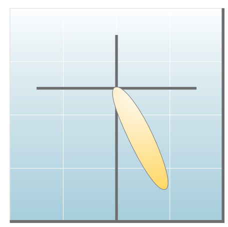


Figure 7-137 – Typical Photometric Distribution, Recreational Sports Luminaire

Description: Recreational sports activities have become so popular that there are demands to provide night lighting to extend playing time. Most sports lighting equipment is mounted on poles outside the playing field.

Lamping: Lamps for sports lighting equipment include metal halide (section 6.6.2).

Materials: Housings should be rated for outdoor use and designed to minimize insect infiltration.

Operation and Maintenance: Locate luminaires where they can be easily accessed with lifts or ladder for maintenance.

Efficiency: Look for shielded luminaires that exceed 45% for a NEMA 2x2 and exceed 60% for a NEMA 5x5.

Design and Control Considerations: For high aerial sports such as baseball and softball, the luminaires need to be located high above the fields (70–100 ft) in order to safely light the field with minimal light trespass. Other aerial sports such as tennis, football and soccer require pole heights that will uniformly light the court or large playing fields yet will discourage high aiming angles. The lower the pole, the higher the aiming angle and the greater the light trespass potential (refer to section 3.2.4).

Adjustable floodlights should be equipped with internal and external shielding. Floodlight photometric distribution types are NEMA type 1, 2, 3, 4, 5, 6 and 7. Type 1 is a very narrow beam (10–18 degrees) while type 6 is a very wide flood (100–130 degrees). The most typical distribution types are 2, 3 and 5. Distributions are classified by their spread in two directions, as in a 2 ft x 2 ft or 3 ft x 4 ft or 5 ft x 5 ft. Tennis courts and other small area playing fields may incorporate IESNA cutoff roadway luminaires in lieu of adjustable floodlights.

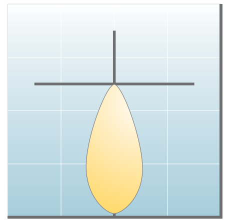


Figure 7-138 – Floodlighting Distribution Pattern

A typical sports lighting design should include equipment layouts with floodlight locations, distribution type and aiming angles. Aiming angles above 60 degrees is discouraged since these floodlights have the greatest light trespass and pollution potentials. (See *IESNA Lighting Handbook, 9th Edition*, chapter 20.)

It is important to design automatic controls to turn off the sports lighting equipment when the fields are not in use to minimize adverse environmental effects. Refer to chapter 8 for thorough information about controls.

7.7 Specialty Lighting Products

Three types of specialty light products are discussed in this section: fiber optic lighting systems, light pipes, and light-emitting diodes (LED).

FIBER OPTIC LIGHTING SYSTEMS

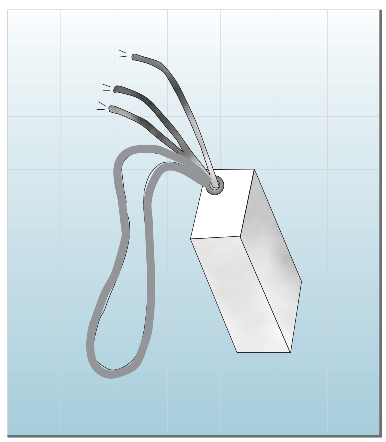


Figure 7-139 – Fiber Optic System

Description: Fiber optic systems are also called “remote lighting systems.” They consist of a light source in a box called an “illuminator,” with a system of optical fibers conducting light from the box out to the end of the fibers. Each fiber has an outer clear “cladding” that provides the difference in index of refraction that allows highly efficient internal reflection inside the fiber. There may be a fixture, or “emitter” located at the end of the fiber, which controls the distribution of light from the fiber. The optics inside the box should be sophisticated, in order to collect light from the source and direct it onto the aperture (“port”) where the fibers are fed from the box. The fibers may be end-emitting, similar to a point-source downlight; or side-emitting, similar to a glowing flexible tube.

There are great advantages to fiber optic lighting systems. It is a way to conduct light without the hazards of electricity; it minimizes the number of different light sources that must be installed and maintained; the fibers conduct light with almost negligible UV and IR components; and the systems frequently have an attractive, unusual, contemporary appearance.

Lamping: Point sources are important to the efficiency of the system. Single-ended compact metal halide, halogen and LED sources are most common.

Materials: Fibers may be made of several kinds of plastic or glass, and each has its advantages and disadvantages for different applications. Stranded glass fibers are more heat resistant, and more flexible in tight bends than stranded plastic fibers. Plastic is more susceptible to damage by ultraviolet and near-UV wavelengths. However, large diameter plastic fibers are the most efficient means to conduct light, with fewer light losses along the length of the fiber. Reflectors in the illuminator often use dichroic-coated glass to direct visible light to the aperture, while allowing the heat to pass through the reflector so that it does not concentrate heat onto the port where plastic fibers may be located. Plastic fiber systems may have a glass interface between the illuminator and the fiber bundle to help dissipate heat, in order to preserve the plastic fibers.

Operation and Maintenance: Theoretically, fiber optic systems should be simple to maintain because there are fewer lamps to change, no aiming to redo, and no moving parts. The reality is that the fibers often degrade because of heat or UV, the color of the light may be negatively affected, and the changing of the lamp in the illuminator may alter the distribution and intensity of light from fiber to fiber. The quality of the system is very much dependent on the quality of the selected equipment and on its installation. Excellent quality installations can remain trouble-free for years.

Efficiency: Although dramatic improvements in efficiency have been promised, the best of these systems are only as efficient as halogen lamps in delivered lumens-per-watt. However, efficiency is seldom the principal reason for specifying them. Even when starting with a highly efficient light source such as metal halide, there are significant collection losses in the interface between lamp/reflector and port; losses between port and the ends of the fiber; losses along the length of the fiber; and losses in delivering that light through a luminaire to its final destination.

Design and Control Considerations: Because they are low in efficiency, fiber optic systems should only be used in places where they work best: where running electricity is a safety hazard (such as in swimming pools or along gangways to ships); where tiny points of light will produce a dramatic effect (such as starlit ceilings or jewelry cases); where UV and IR need to be minimized (such as in museum cases with fragile objects); or where the appearance of the end-lit or side-lit fiber contributes spectacularly to the design appearance. Individual control of each fiber's output is difficult because it reduces efficiency of the system. If controls are desired, color wheels or template wheels can be installed at the port end of the illuminator.

LIGHT PIPES

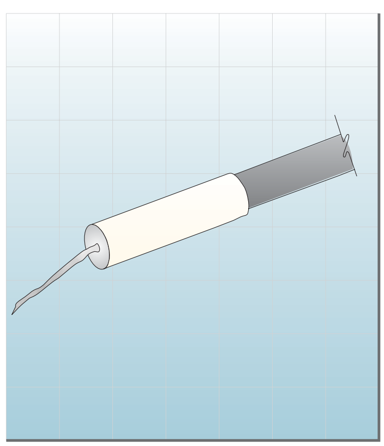


Figure 7-140 – Light Pipe

Description: Like fiber optic lighting systems, light pipes are another form of remote source lighting. The electric lamp is located in a housing that directs its light toward an aperture. A long tube is then mounted to the aperture, which transmits light down its length following the principles of "total internal reflection." The tube then has sections designed to extract the light, usually through refracting or diffusing lenses cut into the sides or ends of the tube. Daylight can also be used instead of an electric lamp.

Lamping: Point-source lamps or the sun are most effective. Single-ended clear metal halide lamps (section 6.6.2) up to 400 watts are most common, although halogen lamps (6.4) are a less-efficient option.

Materials: The light pipe can be made of several materials: an extruded acrylic with linear 45-degree prisms, in a round or square shape (usually 4 or 6 inches in diameter or square); a round plastic tube lined with a special reflective prismatic film (usually 3 to 9 inches in diameter); or a large-diameter metal tube with a highly specular silver interior coating. In the latter case it is critical that the interior coating have a reflectance of 95% or greater.

Operation and Maintenance: Light pipes must be carefully sealed so that they are impenetrable to dirt. Otherwise, total internal reflection is quickly compromised.

Efficiency: Efficiencies of the system are strongly dependent on the length of the pipe, the cleanliness of the pipe, the ability of the illuminator to collect light into a very narrow angle, and the illuminator-pipe interface.

Design and Control Considerations: Light pipes are an excellent choice when there are accessibility issues or safety issues that would prevent the use of more traditional (and more efficient) lighting systems. Examples are explosion-prone areas where electric sparks must be eliminated, or areas above a swimming pool where it is difficult to reach luminaires for maintenance. Because there are not many light distribution options from the extractor or lensed section of the light pipe, the designer must consider whether the light pipe system is delivering the desired light distribution for the application.

LIGHT-EMITTING DIODES (LED)

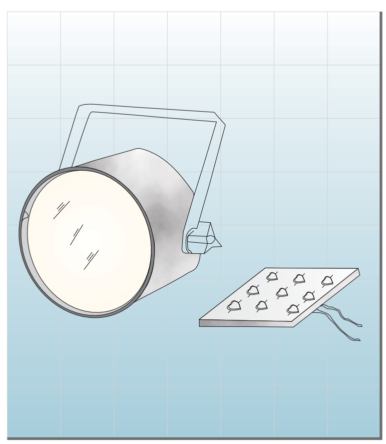


Figure 7-141 – Light-emitting Diodes (LED)

Description: LEDs are a promising lighting technology for architectural applications. These very small, solid-state devices are the same LEDs used as indicator lights in electronics for many years. However, recent technology developments have produced a wider range of colors (red, orange, yellow, amber, green, blue), and the blue LED emits enough short-wavelength energy to excite phosphors to produce white light. There are also products that combine the light of red, green and blue LEDs to produce a white light. Although the color-rendering ability of these "white lights" is limited at the time of this writing, improvement is expected soon. LEDs are frequently used as energy-efficient replacements for red and green traffic lights.

Lamping: Solid-state LEDs are mounted on a PC-board or chip. LEDs require a power supply, running at voltages between 3 V and 24 V. LED light sources are discussed in detail in section 6.7.

Materials: Luminaires using these sources may be long metal strips to which the small PC-boards are mounted, or conventional-appearance track heads that house arrays of LEDs.

Operation and Maintenance: A minimum of maintenance is associated with LEDs because “lamp life” is often as much as 100,000 hours. More of an issue is lamp lumen depreciation, since the light output decreases steadily over life. This depreciation varies widely according to the type of technology used.

Efficiency: Lumens-per-watt is a poor way to describe the efficacy of a colored light source. LEDs are low in classical efficacy, but are a very efficient means to produce colored light. Because luminaires using LEDs are used for very specialized applications requiring color, the luminaire efficiency is less important than achieving the desired effect with a minimum of input watts. It is impossible to recommend a minimum efficiency value when the applications vary so widely.

Design and Control Considerations: LEDs deliver a narrow beam of intensely colored light. They can be easily dimmed and combined with other colors of LEDs to produce a wide range of colors. The color change can be dynamic. For short-throw applications such as cove uplighting, shelf lighting, shop-window color changes, or dramatic color effects in low-ambient conditions (such as restaurants and night clubs), LEDs are a viable technology.

7.8 Exit and Egress Luminaires

Emergency lighting regulations have evolved in response to building fires and other events that led to injury and loss of life to occupants. When a building is evacuated, occupants—including those who are unfamiliar with the building—must be able to find exit doors and stairways that will lead them away from harm. The Uniform Building Code (UBC) and the National Fire Protection Association (NFPA) Life Safety Code provide regulations and guidelines, but it is also important for the designer to select luminaires that are visible under the five following conditions: during daylight hours when normal lighting is on or off, during nighttime hours when normal lighting is on or off, and in smoke-filled environments. Refer to the Lighting Research Center’s Specifier Report on exit signs (Boyce 1994) for issues of exit sign visibility.

LED Exit Signs

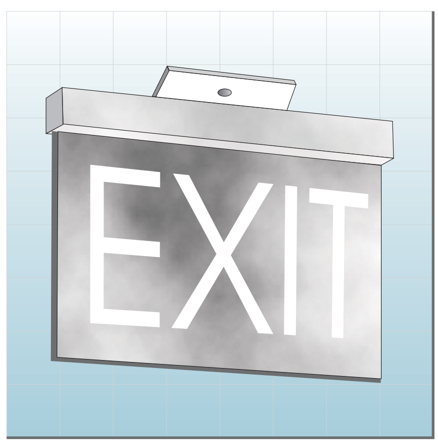


Figure 7-142– LED Exit Sign

Light-emitting diode (LED) technology in exit signs provides significant benefits over incandescent and compact fluorescent technology. The life of LEDs far exceeds that of incandescent and fluorescent. LEDs have low power requirements, which allow smaller battery sizes and slimmer sign dimensions. Innovative exit sign designs use internal reflectors, diffuse interior surfaces, higher light output LEDs, and colored diffusers to reduce the number of LEDs required, thus reducing the sign’s power consumption. The U.S. Environmental Protection Agency's Energy Star exit sign criteria is 3W/face for red letters; 7W/face for green letters. LED light sources are treated in section 6.7.

Photoluminescent Exit Signs

Photoluminescent materials are a technology that may evolve to be widely useful for exit signs. The sign's luminous panel requires no electrical connections. It is "charged up" not by electricity, but by normal ambient light, usually requiring a minimum of 50 lux (5 fc). When the normal ambient illuminance is extinguished because of power failure or earthquake or other emergency, the signs continue to radiate light, decaying in their light output over a few hours. Older technologies, such as copper-activated zinc sulfide produce very low initial luminances. Newer photoluminescent materials using strontium aluminate with rare-earth activators show promise in producing higher initial luminances. These may be applicable in places where the National Fire Protection Association allows low-luminance signs, such as hazardous locations where normal electrical wiring would pose a spark hazard.

As with any exit sign, they should only be used when permitted by local building codes. Ambient temperature and ambient illuminance on the sign are critical factors to be considered. For more about photoluminescent materials, see section 6.8.

Emergency Lighting

Full-size and Large Compact Fluorescent

Improved compact-size fluorescent emergency ballast technology is available to fit into the smaller luminaires using T-5 lamps. These emergency ballasts are equipped with a sealed rechargeable long-life battery and will operate one T-5 or T-8 lamp for up to 90 minutes in the event of a power failure. Lumen output will vary depending on the ballast selected. Typical values range from 500 to 825 lumens. The ballasts are fitted with a one-piece test switch and light to comply with code requirements. See section 6.5.3 for information about fluorescent ballasts.

Flip-down MR-16 Luminaires

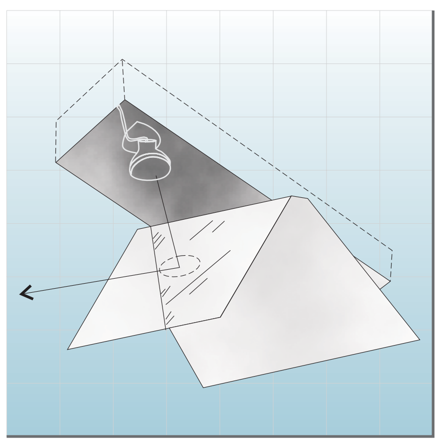


Figure 7-143 – Concealed Emergency Lighting

A novel category of egress lighting utilizes MR-16 halogen lamps. The luminaires remain concealed behind discreet doors in the ceiling or walls until power fails, when the doors "flip down" from the ceiling or out from the wall to illuminate exit pathways. Under normal conditions the luminaire face is a metal panel that may be painted or covered with a wall covering to match the wall finish. These units are provided with an accessible test switch and a visible charging light recessed in the enclosure. By remaining hidden from view during normal operation, these luminaires provide a design alternative to traditional "bug-eye" units.

7.9 The Lighting Retrofit Opportunity

Many existing lighting installations may be upgraded through a lighting system retrofit. As discussed comprehensively in the *Lighting Retrofit Manual* (EPRI 1997), lighting retrofits provide an opportunity to improve lighting quality, reduce electricity demand and maintenance costs and save energy, providing environmental benefits. Lighting retrofits may involve the replacement of luminaire components such as lamps, ballasts, sockets, reflectors and shielding media or may involve redesign of the lighting system with new luminaires. This section discusses several advanced design concepts for lighting retrofits (see section 4.4.3 for information about economic analysis of lighting retrofits). For a complete discussion of the lighting retrofit process, refer to the *Lighting Retrofit Manual*.

It's important to review and develop criteria for retrofit lighting design and maintenance before performing lighting retrofit design and installation. In many instances the use of the space or area may have changed from its original use. The proposed retrofit must be responsive to the current design criteria and intended use. It's also important to take advantage of the existing conduit and/or wiring system whenever possible. In some instances, it may be necessary to minimize the work above an existing ceiling because of the presence of asbestos.

Advanced lighting retrofit products include high efficacy lamp/ballast systems, excellent luminous distribution characteristics and improved maintainability as compared to the existing lighting system. While it is important to select the most effective products appropriate for the design application, it is essential to address the spatial design parameters concurrently. Room and background and surround reflectances should be specified appropriately to achieve a successful retrofit lighting installation.

7.9.1 Interior Lighting Retrofits

Significant improvements in lighting system performance can result from interior lighting retrofits. Advanced lighting retrofits reduce energy use and improve system efficacy, light distribution, color rendering properties and maintenance factors.

When deciding to retrofit luminaires, consider the importance of design criteria such as flicker, direct glare, light distribution on room surfaces, color appearance, and other criteria. These criteria are described in chapter 4 these Guidelines and in chapter 10 of the *IESNA Lighting Handbook, 9th Edition*.

Refer to EPRI's *Lighting Retrofit Manual* for specific recommendations for commercial and industrial applications. Technology recommendations discussed in the *Lighting Retrofit Manual* for the majority of common luminaires include:

- Ballast conversions
- Lamp conversions
- Reflector replacements
- Shielding and diffusing media replacements

Full-size Fluorescent Retrofits

Adding a Specular Imaging Reflector

The traditional lensed troffer can be retrofitted with a specular imaging reflector. The efficiency of a two-lamp, 2 ft x 4 ft, reflector-equipped luminaire, consisting of a pattern-12 (standard) prismatic lens, and properly aligned lamps, rises from about 70% to about 80% with the addition of a specular imaging reflector because more light is directed downward. CU-factors increase, but spacing criteria usually decrease. (This means that uneven lighting on the work plane may result if the existing spacing is not altered. The designer must verify that the SC of the new reflector accommodates the existing luminaire spacing.) The increase in efficiency and CU is greatest when the reflector is designed exactly for the luminaire and the desired light distribution.

Most common lens types, such as prismatic, batwing, linear batwing, and polarized can be used, although not all types will exhibit increased efficiency when used with a reflector. Final photometric performance—especially uniformity of illumination—may be altered significantly when compared to traditional painted troffers. Some efficient luminaires use the specular materials listed above in carefully contoured reflectors for maximum control and efficiency. These materials are also used in specular imaging reflectors, designed as retrofit components to be inserted into existing luminaires.

Relamping and Delamping

In theory an existing three- or four-lamp fluorescent troffer, for example, can have one or two lamps removed, and some of the lost light output can be recovered through the use of a "one-bounce" or specular reflector. The specular reflector replaces the troffer's original white-painted reflecting surface. By removing a lamp from a four-lamp troffer and inserting an optically superior specular reflector, it’s possible to recover efficiency losses due to degradation of the original white paint and reduce the amount of light and heat trapped in the luminance. This typically results in approximately the same light output from three lamps as from four without the reflector.

When reflector replacement is combined with relamping of a luminaire's aging lamps, and cleaning of the luminaire surfaces, light output may actually be greater than it was prior to the retrofit. In addition, by further improving lamp-ballast combinations, more dramatic delampings can be performed. However, use of reflectors with delamping will almost always change the original candlepower distribution pattern of the luminaire, which may or may not be desirable, depending on the application.

Often spaces are overlighted to the extent that lamps can be removed without adding a reflector while maintaining adequate illumination. In these cases, reflectors may still be considered because, with a reflector, the luminaire’s lens is more uniformly bright, and the luminaire does not appear as if some of the lamps are missing.

Specular reflectors are also offered in a number of new troffers. However, the efficiency improvements due to these reflectors are not as dramatic when compared to the retrofitting of white-painted reflectors, because some of the advertised effectiveness of these reflector products is due to improvements over poorly shaped and/or deteriorated, painted reflector surfaces in old luminaires.

CFL Screw-in Retrofits

Techniques are available for retrofitting incandescent downlights to compact fluorescent technology. Except for the means of connecting power, these designs have elements used in conventional luminaires: lamp holders with replaceable lamps and housings for the ballast and other components. Some designs make use of the incandescent lamp holder's medium-base screw-shell for mounting and power connection. Some designs are also equipped with reflectors and/or lenses to improve light distribution and provide shielding (see Figure 7-144). The reflector and lens assembly is designed to correctly match the lamp for optimum performance. Also, the lamp can be replaced without replacing the rest of the assembly, reducing the chance that an incandescent lamp will be substituted later.

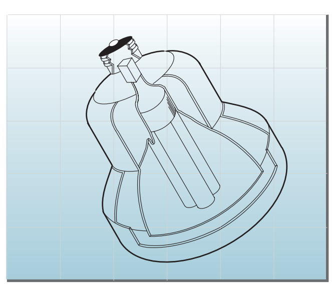


Figure 7-144 – Screw-in Compact Fluorescent Luminaire

Take care when specifying these types of luminaires. Since Underwriters Laboratories (UL) considers them "lamp holder accessories," the thermal testing procedure common to luminaires does not apply. It is particularly important that the specifications call for the lamp to perform within the manufacturer's limits when the unit is operated in its intended application. Key specification items include the lamp operating current, lamp compartment temperature, and the lamp base temperature. In general, these types of luminaires cannot be used with dimmers. (For more about compact fluorescent sources, see section 6.5.6.)

Permanent Compact Fluorescent Conversions

Realizing the inadequacies and impermanence of screw-in compact fluorescent adapter kits, manufacturers have introduced compact fluorescent kits for permanent remodel use. These kits include efficient reflectors, properly positioned and shielded lamps and, in some cases, electronic ballasts. Many major companies who make standard incandescent downlights are now producing compact fluorescent conversion kits specially designed to upgrade their existing products. These kits offer the advantage of extremely rapid conversion. Non-OEM (original equipment manufacturer) companies, on the other hand, make kits to convert many existing 5–7 in. aperture incandescent luminaires. These products are supplied with universal conversion kits. Again, specifiers should be aware that some types of conversion kits may not be UL-listed and/or may void listing of the assembly once installed. Care should be taken in the specification process. For more detail, see the *Lighting Retrofit Manual* (EPRI 1997)

Toplighting

Adding skylights to an existing building is often possible. Excellent examples include open structures such as warehouses, vehicle repair and storage garages, “big box” retail, loft buildings and manufacturing plants. The addition of skylights in these types of facilities may be relatively simple because the ceiling is open to the roof and the roof structures typically are framed with trusses or beams and joists that can be altered to provide the necessary openings for skylights. See section 7.4 for a complete discussion of daylight systems, including advanced skylight design.

As part of the decision to perform a skylight retrofit, it's important to review the electric lighting system. Installing skylights provides the opportunity to reduce the electric lighting energy use. However, if the existing electric lighting system is not controlled, the energy benefits of the skylight retrofit will not be realized. See section 8.4 for a complete discussion of controlling luminaires in daylit areas.

7.9.2 Exterior Lighting Retrofits

Installation of full cutoff luminaires

The exterior lighting environment may be improved through the replacement of non-cutoff exterior luminaires with full cutoff types. In existing applications already using high efficacy sources with non-cutoff luminaires, the use of full cutoff luminaires may improve the effectiveness of the lighting system through improved uniformity and reduced glare, light trespass and light pollution. In such retrofit applications the use of existing luminaire locations may save wiring and site improvement costs. Final luminaire locations must be determined based upon considerations of uniformity and illuminance, while minimizing light trespass and light pollution.

For pole-mounted applications, efficient full cutoff luminaires may be selected in a variety of IESNA distributions to suit the existing pole spacing. Metal halide and high-pressure sodium sources may be used to improve system efficacy over existing mercury vapor systems. In many cases the existing poles may be retrofitted with new luminaires. When new poles are selected for use at existing pole locations, the existing concrete pole bases must be reviewed for structural adequacy. Also, the existing anchor bolt patterns may require special pole bases or adaptors to allow attachment of new poles.

For building-mounted applications, full cutoff luminaires may directly replace:

- Non-cutoff, refractor-type “wall packs” on building facades
- Floodlights on building facades

- Refractor-type area lights mounted under open canopies and exterior building soffits

7.9.3 Application Correction Factors

For the purposes of giving guidance in retrofit applications, the Advanced Lighting Guidelines has combined BFs and TFs into the application correction factor, which accounts for luminaire type and mounting conditions. The Application Correction Factor was introduced with the 1993 Advanced Lighting Guidelines and provided useful data on how applications affect input watts and lumen output. Since the application correction factors were published in 1993, many manufacturers have begun to publish performance data for specific ballasts and luminaire combinations, making the data in these tables less important. Application correction factors are not used n the IESNA Handbook or other reference sources.

The application thermal factor tables give information that will enable the designer to assess the total luminaire system performance, and that enable the engineer or energy auditor to make more accurate estimates of system energy use. Without considering these correction factors, an energy estimate for a lighting design could easily be off by up to +/- 15%.

The columns of the tables are typical luminaire installations, labeled A through G for full-size fluorescent lamps and H through P for compact fluorescent lamps. The rows of the tables show groupings by lamp-ballast combinations.

The Application Correction Factor represents the most significant portion of total non-recoverable light loss for a given luminaire. For instance, the first lamp-ballast combination in Table 7-4 is the standard F40T12 lamp with a standard energy-efficient (manufactured after 1990) magnetic ballast with a ballast factor of 0.94 for the test conditions. The application correction factor is given for this lamp-ballast combination for the nine different luminaire installations (labeled A through G), and shows a range of actual light output differing -5% to +11% from ANSI values.

The table also gives the input-watts for common lamp installations, in this case, four lamps, three lamps or two lamps. The table also gives input-watts separately for one-, two- or three-lamp ballasts when this is appropriate. Descriptions of the luminaire installations and other assumptions about the luminaires are provided below in the Assumptions section.

The application correction factor should be used to correct an appropriate photometric report for the application condition. If a photometric report exists for a specific luminaire equipped with one of the lamp-ballast combinations listed in the tables, then the CU (and luminaire efficiency value) listed for that luminaire in the report may simply be multiplied by the appropriate application correction factor listed in Table 7-4 or Table 7-5 to estimate the effects of ballast factor and thermal factor on lighting system performance. Recoverable light loss factors due to lamp lumen depreciation or dirt accumulation must be accounted for separately using standard procedures.

The ballast factors assumed for each combination are clearly noted in the tables. Generally, these ballast factors are estimates of 1992 "industry-average" ballast factors for each respective lamp-ballast system. If the ballast factor for an intended lamp-ballast combination is substantially different from the listed value, the input power values can be determined simply by applying the following equation:

$$\text{Corrected input power} = \text{Listed input power} \times \frac{\text{Intended ballast factor}}{\text{Listed ballast factor}}$$

Equation 7-5

Table 7-4 – Luminaire System Performance, Full-Size Fluorescent Lamps

	Luminaire Type	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Lamp/Ballast Type	**Luminaire Description**	**Recess Static Open**	**Recess Static Closed**	**Recess Heat Extract**	**Surface Closed Uninsul.**	**Surface Closed Insulate**	**Surface Open / Suspend Closed**	**Suspend Open ANSI**
F40T12, Magnetic Energy-Efficient Ballast, Ballast Factor: 0.94	**Application Correction Factor**	0.9	0.9	1.04	0.94	0.89	0.94	0.94
	Input Watts:							
	4 lamps (2) ballasts	161	160	174	160	150	172	176
	3 lamps (2) ballasts	123	121	133	121	114	131	134
	3 lamps (T) ballasts	121	120	131	120	113	129	132
	2 lamps (1) ballast	81	80	87	80	75	86	88
34-Watt F40T12/ES Lamps, Magnetic Energy-Efficient Ballast, Ballast Factor: 0.87	**Application Correction Factor**	0.85	0.83	0.95	0.87	0.83	0.87	0.87
	Input Watts:							
	4 lamps (2) ballasts	140	137	144	140	135	144	144
	3 lamps (2) ballasts	109	107	112	108	105	112	112
	3 lamps (T) ballasts	105	103	108	105	101	108	108
	2 lamps (1) ballast	70	68	72	70	68	72	72
FB40T12 Lamps, Magnetic Energy-Efficient Ballast, Ballast Factor: 0.94	**Application Correction Factor**	0.9	0.9	1.04	0.94	0.89	0.94	0.94
	Input Watts:							
	3 lamps (2) ballasts	123	121	133	121	114	131	134
	3 lamps (T) ballasts	118	117	128	117	110	126	129
	2 lamps (1) ballast	79	78	85	78	73	84	86
F40T12 Lamps, Electronic "Standard" Rapid Start Ballast, Ballast Factor: 0.88	**Application Correction Factor**	0.85	0.85	0.96	0.88	0.84	0.88	0.88
	Input Watts:							
	4 lamps (2) ballasts	136	133	142	133	125	143	144
	3 lamps (1) ballast	101	99	106	99	93	106	107
	2 lamps (1) ballast	68	67	71	67	63	72	72
34-Watt F40T12/ES Lamps, Electronic "Standard" Rapid Start Ballast, Ballast Factor: 0.88	**Application Correction Factor**	0.87	0.85	0.94	0.88	0.84	0.88	0.88
	Input Watts:							
	4 lamps (2) ballasts	124	120	126	122	118	125	124
	3 lamps (1) ballast	90	87	91	89	86	91	90
	2 lamps (1) ballast	62	60	63	61	59	63	62
FB40T12 Lamps, Electronic "Standard" Rapid Start Ballast, Ballast Factor: 0.84	**Application Correction Factor**	0.81	0.81	0.91	0.84	0.8	0.84	0.84
	Input Watts:							
	3 lamps (1) ballast	94	93	99	93	87	99	100
	2 lamps (1) ballast	63	62	66	62	58	67	67
F40T12 Lamps, Electronic Reduced Output Rapid Start Ballast, Ballast Factor: 0.71/0.73	**Application Correction Factor**	0.69	0.69	0.77	0.71	0.68	0.71	0.71
	Input Watts:							
	3 lamps (1) ballast	85	83	89	83	78	90	90
	Application Correction Factor	0.71	0.71	0.79	0.73	0.7	0.73	0.73
	Input Watts:							
	2 lamps (1) ballast	57	57	60	57	53	61	61

Table 7-4 – Luminaire System Performance, Full-Size Fluorescent Lamps (continued)

Notes:

(*) = Estimated change in lamp ambient temperature between photometric test condition and application condition
(1) = 1 ballast per luminaire
(2) = 2 ballasts per luminaire
(T) = Tandem wiring for three-lamp luminaires, average 1.5 ballasts per luminaire
Three-lamp luminaires with magnetic ballasts have 1 single-lamp ballast and 1 double-lamp ballast

Description of Luminaire Installations

A – Generic large cell "parabolic" troffer recessed into acoustic tile grid ceiling with little or no air movement around the luminaire.

B – Generic closed troffer with flat prismatic lens recessed into an acoustic tile ceiling.

C – Same as "A," except luminaire is of the heat extract type where the HVAC system draws return air through the luminaire. These data may also be used for luminaire installation "B" if it is of the heat extract type.

D – Surface mount commercial luminaire with "wraparound" lens, mounted to uninsulated gypsum board ceiling (for U-lamps, a commercial flat lens luminaire is assumed).

E – Same as "D," except the ceiling is insulated.

F – Open-mounted strip-light surface mounted to uninsulated gypsum board ceiling or Tubular fluorescent suspended luminaire, lensed indirect, enclosed top, suspended 2 ft below the ceiling.

G – Square-section fluorescent luminaire with open top uplight in free air at 25°C (77°F). This situation most closely resembles ANSI standard test conditions for full-size fluorescent lamps so the lamp lumen output and ballast factor most closely correspond to the catalog values.

Table 7-5 – Luminaire System Performance, Compact Fluorescent Lamps

Lamp/Ballast Type	Luminaire Description	H Recess Unvent Base Up	I Recess Vented Base Up	J Recess Unvent Horiz.	K Recess Vented Horiz.	L Surface Closed Uninsul	M Surface Closed Insul.	N Wall Open Uninsul	O Wall Closed Jar	P Free Air ANSI Table
9 Watt Twin-Tube Lamps, 120 Volt Standard Reactor Ballast, Ballast Factor: 0.85	**Application Correction Factor**	0.82	0.84	0.81	0.84	0.83	0.80	0.83	0.83	0.85
	Input Watts:									
	1 lamp (1) ballast	13	13	13	13	13	13	13	13	13
	2 lamps (2) ballasts	26	26	25	26	25	25	26	26	26
13 Watt Twin-Tube Lamps, 120 Volt Standard Reactor Ballast, NPF, Ballast Factor: 0.90	**Application Correction Factor**	0.87	0.89	0.85	0.89	0.88	0.84	0.88	0.88	0.90
	Input Watts:									
	1 lamp (1) ballast	16	16	16	16	16	16	16	16	16.5
	2 lamps (2) ballasts	32	33	32	33	32	32	33	32	33
13 Watt Quad-Tube Lamps, 120 Volt Standard Reactor Ballast, NPF, Ballast Factor: 0.90	**Application Correction Factor**	0.87	0.89	0.85	0.89	0.88	0.84	0.88	0.88	0.90
	Input Watts:									
	1 lamp (1) ballast	16	16	16	16	16	16	16	16	16.5
	2 lamps (2) ballasts	32	3	32	33	32	32	33	32	33
26 Watt Quad-Tube Lamps, 277 Volt Standard Reactor Ballast, HPF, Ballast Factor: 0.90	**Application Correction Factor**	0.87	0.89	0.85	0.89	0.88	0.84	0.88	0.88	0.90
	Input Watts:									
	1 lamp (1) ballast	32	33	32	33	32	32	33	32	33
	2 lamps (2) ballasts	65	65	64	65	64	64	65	65	66
26 Watt Quad-Tube Lamps, 277 Volt Electronic Ballast, Ballast Factor 0.90	**Application Correction Factor**	0.88	0.89	0.86	0.89	0.88	0.85	0.88	0.88	0.90
	Input Watts:									
	1 lamp (1) ballast	24	25	24	25	24	24	25	24	27
	2 lamp (2) ballasts	49	51	48	50	48	47	51	49	54

Notes:
(1) = 1 ballast per luminaire
(2) = 2 ballasts per luminaire

Description of Luminaire Installations

H – Recessed unvented downlight with vertical base-up lamps and nominal 7 in. aperture recessed in acoustic tile ceiling.

I – Same as "H," except the luminaire is vented to improve thermal performance.

J – Recessed unvented downlight with horizontal lamps and nominal 7 in. aperture recessed in acoustic tile ceiling.

K – Same as "J," except the luminaire is vented.

L– Surface-mounted "vandal resistant" luminaire (enclosed) on uninsulated gypsum wallboard ceiling.

M – Same as "L," but insulated ceiling.

N – Open top wall sconce, surface mounted to uninsulated wall.

O – Enclosed and gasketed wall bracket, industrial "jelly jar" type luminaire.

P – Free air table lamp, essentially ANSI/catalog values.

Assumptions for Application Correction Factor Tables

To generate the tables, certain assumptions were made about the features of the space where the lighting system is located. These assumptions are common to both and Table 7-5 and are listed below.

- All luminaires are static (not heat extraction type) unless otherwise indicated.
- Where indicated, "acoustic tile ceiling" assumes a lower floor of a multistory building, with ducted supply and return plenum.
- Where indicated, "gypsum wallboard ceiling" assumes lower floor of a multistory building if not insulated; otherwise assumes residential style construction in a single-story building.
- Air movement and temperature maintained by the HVAC systems is typical of a variable air volume system in office occupancy. Room temperature is maintained at 25°C (77°F).
- Plenum temperature is assumed to be 30°C (86°F).
- For Table 7-4, the relationship for the various luminaire-lamp-ballast systems between lamp lumen output and ambient temperature, and between system input power and ambient temperature are taken from Bleeker 1990. Since thermal performance data of lamp-ballast systems using the T-5 lamp was not available
- The thermal performance of the T-5 systems is assumed to be the same as for the T-8 systems. This table will be amended at a later date when more data become available.

The thermal performance data for Table 7-5 is from unpublished Lawrence Berkeley National Laboratory data.

The estimated lamp ambient temperatures for all nine luminaire categories are listed at the end of Table 7-4 for the magnetic pre-1990 ANSI/CBM ballasts driving F40 and F40ES lamps. The temperatures listed for the F40 system are used for all the F40 lamp systems. All other systems use the temperature values for the F40ES lamp systems.

- The estimated change in lamp ambient temperature that results in going from the application condition to the luminaire photometric condition (see row labeled "ΔT LM-41→app") are listed for the F40 and F40ES lamps operated on magnetic pre-1990 ANSI/CBM ballasts. The temperature changes for the F40 lamp system are used for all F40 lamp systems. The temperature changes for all other systems use the ΔT values for the F40ES lamp system. Note that, except for the heat extract luminaire, these ΔTs are positive (or 0); i.e., the lamp ambient temperature is generally higher under the application condition than under the photometric test condition.
- For heat extract luminaires (luminaires in which return air is drawn through the lamp compartment), the reduction in ambient temperature around the lamps, relative to the lamp ambient temperature obtained in the photometric test condition, is assumed to be 9°C (16°F) for full-wattage F40 lamps and 7°C (13°F) for F40ES lamps.

7.10 Luminaire System Performance

The luminaire system consists of reflectors, lenses, refractors, housings and gasketing (described in section 7.2), as well as the lamps and ballasts (described in chapter 6). System performance depends on how well all these components work together. With the introduction of many new products—especially electronic ballasts—designers must pay special attention to the interactions between lamps, ballasts and luminaires.

Thermal effects, in particular, vary widely and affect luminaire-lamp-ballast system performance. With fluorescent lamp-ballast systems, light output (lumens), input watts and efficacy are all sensitive to changes in the ambient temperature. When the ambient temperature around the lamps is significantly above or below 25°C (77°F), the performance of the lamp-ballast system can change significantly.

Figure 7-145 shows this relationship for two common lamp-ballast systems: the F40T12 lamp with magnetic ballast and the F32T8 lamp with electronic ballast.

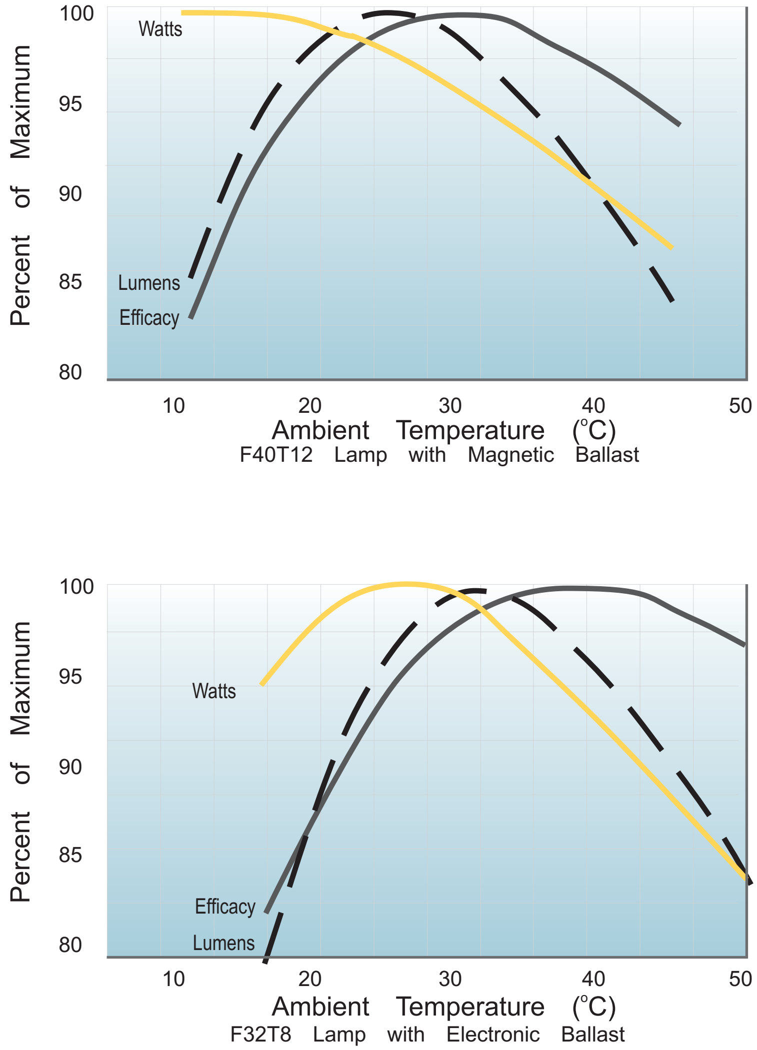


Figure 7-145 – Sensitivity of Lamp-Ballast Performance to Ambient Temperature

Figure 7-145 shows that the optimum operating temperature for the F32T8 lamp-ballast system is 10°C (18°F), higher than the F40T12 system. This means that for installations when the lamp ambient temperature is greater than 25°C (77°F), the light output and efficiency of the F32T8 system is actually higher than performance under the rated ANSI conditions. Similarly, performance of lamps with even smaller diameters, such as T-5 twin-tube lamps, peaks at even higher ambient temperatures.

7.11 Guideline Specifications

Lighting specifications for luminaires should be carefully written to avoid the substitution of inferior products that might sacrifice energy savings. A good specification can ensure the comfort, quality, and energy efficiency of the lighting design.

7.11.1 Proprietary and "Three-Name" Specifications

There are two methods of specifying luminaires. The easiest is to give the make and model number of the luminaire in the lighting fixture schedule. This type of specification is often called a proprietary specification because the basis of the specification is a certain manufacturer's product.

Most governmental agencies and corporations require that more than one product be specified. Often at least three "equal" products must be listed. Since many advanced products are not generic, most agencies allow the specifier to list only the one product—the one that served as the basis of design—provided that the specifier can demonstrate that the product is unique, and that the specifier has no vested interest in that product.

Table 7-6 – Sample Specifications for Project XYZ

Tag	Description	Lamps	Ballast	Input Watts	Volts	Product
F1	Recessed parabolic troffer 2' X 4', 3" deep 18 cell specular clear louver, black floating door, slotted grid NEMA NFSG mechanical unknown	(3)F32T8/RE735	Modified rapid start electronic 265 MA with BF> .85	93	277	ABC-123-3F32-Elec-GT-277 DEF-345-3F32-Elec-GT-277 GHI-678-Elec-GT-S-332-277
F2	F2 Suspended uplight continuous aluminum extruded housing in painted finish to match architect's sample. Sample 18" stem with earthquake ball, side lens layout, and lengths per plans	(2)F32T8/RE735 per each 4' length	Instant-start electronic two-lamp or four-lamp as required TTT 440 series	56	277	JKL-F32-LENGTHS

Note: This example shows a type "F1" for which at least three possible products exist that are known to meet the designer's specifications. The type "F2" is a unique product.

7.11.2 Performance Specifications

Instead of specifying a product by name, it's possible to specify a product by thoroughly describing its performance characteristics. Key identifying characteristics are the photometric curves of the luminaire. Like fingerprints, photometric data are virtually unique to each luminaire. Characteristics may include coefficient of utilization, efficiency, distribution patterns, spacing criterion, zonal lumens, and candlepower at specific angles. It's especially important to use a performance specification in cases where visual performance may be impaired by poor luminaire characteristics as in, for example, VDT areas.

It's also advisable to include construction parameters when writing a performance specification. Material gauge, construction method, tolerances, and other quality factors should be included to prevent substitution by photometrically correct but otherwise inferior products.

The performance specification should require certified test data from an independent laboratory or a manufacturer's lab accredited by NVALP, using IESNA or ANSI recommended testing methods. In the highly competitive business of luminaire manufacturing, very few designs are successfully patented, and inferior "knock-off" products are frequently substituted for a well-engineered luminaire. A cheap copy may be acceptable as long as it performs as well as the original, although construction quality may be reduced, causing higher maintenance costs.

7.12 Resources

The Illuminating Engineering Society of North America (IESNA) regularly lists luminaire product offerings complete with lists of features and vendors. For more information, go to IESNA's Web site at http://www.iesna.org (email: iesna@iesna.org) or refer to the IESNA publication *Lighting Design + Application (LD+A),* a periodical having an annual directory of lighting equipment, including luminaires.

The International Association of Lighting Designers (IALD) offers a Guide to Specification Integrity, available at http://www.iald.org.

The National Electrical Manufacturers Association (NEMA) has a Web site with informative documents and white papers at http://www.nema.org.

Other notable lighting publications with product offerings include *Architectural Lighting, Architectural Record* and *Lighting Dimensions.* Many lamp, ballast, controls, components and luminaires manufacturers are excellent resources for information about products and design. You may contact their engineering departments by telephone or check their Web sites.

8. LIGHTING CONTROLS

Controls are an excellent way to reduce lighting energy while enhancing lighting quality. Occupancy sensors can eliminate wasted lighting in unoccupied spaces. Daylighting controls or advanced load management can reduce lighting demand when energy is most expensive. And manual dimmers, which allow occupants to adjust light levels to their preference, are becoming more affordable. Lighting controls have been shown to reduce lighting energy consumption by 50% in existing buildings and by at least 35% in new construction. More discussion of potential savings is provided later in this chapter.

In the past, the common light switch was the primary means of controlling lighting in buildings. However, specifiers are starting to implement more advanced controls due to a reduction in the cost of control hardware and other technological developments. This is resulting in very significant energy savings while offering occupants something in return—better control of their lighted environment. Today, lighting controls are entering a new era, where they will be considered not just for saving lighting energy but as a real amenity for the people for whom buildings are built.

This chapter is organized into six sections. The first section (8.1) addresses user and energy-saving issues related to controls. The next five sections deal with specific control technologies: switches and dimmers (8.2), occupancy sensors (8.3), daylighting controls (8.4), building-level controls (8.5) and other controls strategies (8.6).

8.1 Overview

The positive benefits of controls depend on both the occupants and building managers understanding how the lighting systems and controls work. This section describes lighting control issues that specifiers must be knowledgeable about if controls are to be used as intended.

8.1.1 Occupant Needs

Lighting controls are intended to fulfill two, potentially conflicting, objectives: (1) reduce lighting energy costs and (2) maintain or improve occupant satisfaction and comfort. Except for the most humble of lighting controls—the manual wall switch—lighting controls have historically had little to offer the building occupants. In the past, the occupants' lighting control needs were thought to be adequately served if they could turn their lighting on or off when arriving or leaving work. In the modern work environment, this attitude is no longer sufficient. Changing visual needs are now the norm rather than the exception and controls can help to meet this variety of needs. For example:

- With the widespread use of computers in the workplace, lighting needs and preferences may change from hour to hour and from day to day. Mixed tasks may require different lighting conditions. If occupants have the ability to easily change lighting conditions according to task or even mood, lighting controls can add to occupant comfort and satisfaction. (See section 4.3 for more about design considerations to meet changing visual needs.)
- Modern office workers move around more, since they do not stay in one job as long as they used to and also because workplaces are rearranged more frequently. A flexibly controlled lighting system can accommodate a high relocation or "churn rate." (Refer to section 4.3.2 for further discussion of workplace flexibility needs.)
- A new development in the workplace is the concept of "hot-desking" or “hoteling” where one workstation may serve a number of different people from day to day and week to week. Again, this requires a flexible lighting system that can provide different light levels for different tasks and workers’ needs. This is described in more detail in section 4.3.2.

- Furthermore, as the median age of workers increases, an increasingly large proportion of older workers may want and need higher levels of illumination. Although sensitivity to glare also increases with age, older workers generally need more light, especially for viewing paper tasks with small type. (The effects of aging on vision are discussed in section 2.1.6; design strategies to reduce glare are provided in section 4.3.2.)

While building managers are used to paying attention to the thermal comfort of workers, paying attention to visual comfort is somewhat new. Since the human visual system is so adaptable, workers are less likely to complain about lighting. However, good lighting contributes to overall interior environmental quality, and many employers are realizing that a better environment leads to many benefits, including helping them retain employees.

Most people don't think about lighting or lighting controls unless the lighting is so bad that they can't perform their work. To be acceptable to building occupants, automatic controls must not disrupt normal working activities. A user must be able to control his or her lighting without affecting others. Users should be able to adapt their lighting according to personal preference and need. The use of lighting controls should be intuitive and obvious. While most users will not notice a 15–25% gradual change in illumination, abrupt changes in light level are distracting and should be avoided, especially for occupants performing stationary tasks.

8.1.2 Building Operation

Cognizant building managers use the building lighting control system as a tool to control building operation costs. Since lighting energy is a substantial fraction of electric energy in many buildings, improved lighting controls can have a major positive impact on building energy consumption and peak demand. Savings from lighting controls may come from:

- Reduced electric lighting use
- Reduced peak demand charges
- Downsizing HVAC equipment (reduced first cost)
- Reduced HVAC operating costs
- Lower maintenance costs
- Productivity improvements

Lighting also affects other building loads, especially HVAC. The usual "rule of thumb" is that every watt saved in lighting saves an additional 1/4 watt in avoided HVAC energy (see also section 4.4.3 – Economic Analysis of Lighting Systems).

Lighting controls must be compatible with existing lighting equipment (luminaires, lamps, ballasts and wiring) and not cause premature equipment failure. Since lighting controls components are usually obtained from multiple vendors, the specifier must be knowledgeable about the interactions between lighting controls and lighting equipment. Sometimes these interactions are surprising—for example, specifying the wrong type of ballast may cause premature failure of lighting contact relays. (Chapter 6 discusses light sources and ballasts; chapter 7 discusses luminaires.)

Controls must be reliable and work correctly virtually all the time. An occupancy sensor that misbehaves even once a week (by turning off lights in an occupied room, for example) may be disabled by a disgruntled occupant. A daylight sensor that dims lights too much as clouds move past will be distracting, causing occupant complaints, and may be disabled.

Most controls require commissioning to ensure that they operate according to design intent and are properly adapted to local conditions. With occupancy sensors, the time delay and sensitivity should be adjusted for each workspace; for example, the sensitivity should be set higher in spaces with little occupant movement (such as offices where keyboard entry is the main task). With automatic daylighting controls, the sensitivity to changes in daylight must be set for local room conditions. Initial commissioning may be done by a professional or by the facility management staff, but for best performance, occupants should be involved in fine-tuning control system operation according to their preference.

Since furniture, occupants and activities often change, lighting controls must be flexible and reconfigurable. If a lighting control is hard to adjust or requires frequent “programming” it will probably not be used effectively. Adjustments and tuning of lighting controls should be accessible and understandable to personnel authorized to make such adjustments.

Sensors should not require undue maintenance or drift significantly. Access to photosensors for cleaning should be considered in the specification and design of the system. Controls that have visible indicators or annunciators are useful to informing building personnel as to whether equipment is functioning properly.

8.1.3 Control Selection Guidelines

This section provides an overview of general control strategies and devices, as well as several useful tables to evaluate which strategies and devices are appropriate for various space types. For a more detailed discussion of specific control strategies and devices, see sections 8.2 through 8.6.

Control Strategies

There are several general strategies for using lighting controls to reduce operating costs and improve lighting system functionality:

1. *Occupancy Sensing:* Turning lights on and off according to occupancy as detected with occupancy sensors. Appropriate for unpredictable occupancy patterns. Section 8.3 covers occupancy sensing in detail.
2. *Scheduling*: Turning lights off according to program using programmable relays, timers and other time clock devices. Appropriate for predictable occupancy patterns. Advanced scheduling strategies are discussed in section 8.5.2.
3. *Tuning*: Reducing power to electric lights in accordance with the user needs at the time. Tuning may be accomplished with dimming devices, but bilevel switching of overhead lighting should also be considered, especially when daylight is available. For more about switching and dimming, see section 8.2.
4. *Daylighting:* Reducing power to electric lights or turning lights off in the presence of daylight from sidelighting or toplighting. Daylighting controls (section 8.4) typically employ a photosensor, linked to a switching or dimming unit that varies electric light output in response to available daylight. Bilevel switching should be considered if dimming is not economically justified (see Tuning above).
5. *Demand Limiting:* Reducing electric lighting power during or in anticipation of power curtailment emergencies. During Emergency Alerts periods (see sections 8.1.5 and 8.5.4) lighting loads can be shed either through voluntary curtailment or automatically by the facilities manager or utility service provider.
6. *Adaptive Compensation:* Reducing light levels during the evening to accommodate lighting preferences at night. Adaptive compensation uses dimming devices or switching relays combined with automatic timers or photocells to vary lighting according. For more information, refer to 8.6.1.
7. *Lumen Maintenance:* Compensating for lamp lumen depreciation using a photocell. This strategy is generally deprecated today, as the lamp lumen depreciation from modern building lighting systems is too small to make lumen maintenance economically viable. Lumen maintenance is described briefly in section **6.2.3**, but is not treated further in this chapter on controls.

Control Devices

The above control strategies define *what* the lighting controls do. The control devices are the physical equipment that is installed to implement the desired control strategies in a particular application. The needs of both the lighting users and the facility manager must be considered when developing the lighting control program.

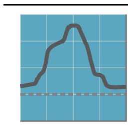
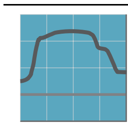
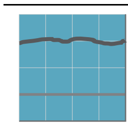
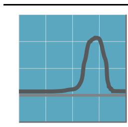
By answering a few questions (see Table 8-1) for each major space type in the application, the specifier can identify what control devices will be required to meet the lighting control program.

Table 8-1 – Recommended Control Devices by Space Use

Ask this about the application:	If YES, consider this device:
Is space use unpredictable? (e.g., unpredictably unoccupied for over 30% of the time; warehouse aisles, hospitality)	Occupancy sensors Timers
Is space use predictable and not a 24-hour, 7-day operation?	Time clock devices
Is exterior lighting used for facades, signage or parking areas?	Photoswitch Time clock devices
Is daylight available from windows or skylights?	Photosensors Photoswitches Multilevel switching
Is there a need to vary light levels during day or after hours?	Manual dimmers Multilevel switching

Control selection should consider the building's expected electric load profile (Table 8-2). For example, daylighting control may be very attractive for a building with peak loads during daylight hours, to reduce demand charges, but not interesting for a building with most of its electric use at night. For this application, adaptive compensation may be a more cost-effective strategy.

Table 8-2 – Selecting Control Devices Based on Expected Lighting Load Profile

Lighting Use Profile		Selection	Devices
	Typical work hours 9 to 5 with limited weekend use	Select controls that reduce peak demand	Occupancy sensors and photosensors for tenant spaces Time clock devices for public areas
	Extended hours	Select controls that reduce unpredictable use	Occupancy sensors Manual dimming/multilevel switching for adaptive compensation
	24-hour	Select controls that reduce lighting day and night	Photosensors Manual dimming/multilevel switching for adaptive compensation
	Event-oriented operation	Manual controls work best	Manual dimming Multilevel switching

Once the control devices have been identified, use Table 8-3 to decide the applicability of the control devices for each space type. Table 8-3 will help narrow the choice of control devices for a building application. However, a building typically consists of multiple space types. For example, a healthcare building might have exam rooms, hallways, private offices and restrooms, each with its own control needs.

For those space types where several control strategies can be applied at once, it is advisable to consider using integrated control systems. Integrated lighting controls provide all necessary control adjustments and inputs at one location. Although integrated controls are somewhat more expensive, the convenience of having one accessible location for performing all system commissioning can reduce setup and maintenance costs. Integrated controls are discussed more in section 8.6.

Table 8-3 – Recommended Control Devices for Different Building Applications

Strategy	**Scheduling**					**Daylighting and Tuning**				
Space Type	Wallbox Occ. Sensor	Ceiling/Wall Occ. Sensor	Personal Occ. Sensor	Timer	Time Clock Device	Multilevel Switching	Manual Wallbox Dimmer	Wireless Remote Dimmer	Photoswitch	Photosensor
Assembly & Light Manufacturing			O		●	O			O	●
Auditoriums		●				O	●	●		
Classrooms		●				●	●	●	O	●
Concourses, Lobbies, Malls					●	●			●	●
Conference Rooms	O	●		O		O	●	●		●
Exterior Lighting		O			●	O			●	
File/Storage Rooms		●		●						
Grocery/Supermarket		●		O	●	●			O	O
Gymnasiums		●				O			O	
Hallways		●			●				●	O
Laboratories		●	O			O	●			●
Library Reading Areas		●			O	O				●
Library Stacks		●		●	O	O				
Locker Rooms		●			O	O				
Lunch/Break Rooms	O	●		O		O			O	
Medical Suite/Exam Rooms	O	●				●	●			
Museums		O				●	●		O	●
Open Offices		O	●		●	●	●			●
Private offices	O	●	●		●	●	●	●		●
Restaurants					O	●	●	O		O
Restrooms	O	●		O		O				
Retail Sales Area					O		O		O	O
Warehouse		●		O	●	●			O	O
● = good application O = limited application										

Manual vs. Automatic Control

Lighting can be automatically controlled (occupancy sensor, timer or photosensor) or manually controlled. Manual lighting control requires no additional hardware and is by far the least expensive. Manual control has been successfully employed in large warehouse or industrial spaces under the watchful eye of a single building manager. In private offices or classrooms where the occupant can adjust the electric lighting according to current daylight conditions, manual controls may be a better solution than automated photocell control strategies.

Automatic control, on the other hand, should deliver reliable energy savings with minimal occupant involvement. Occupancy sensors (section 8.3) reduce wasted lighting hours successfully in many building applications. Photosensor-controlled lighting systems (section 8.4) monitor ambient light levels and automatically reduce electric light levels during times when daylight is available. When designed well, photosensors respond to daylight fluctuations in a way that is not noticeable to occupants and provide balanced electric lighting with minimal energy usage. But automatic controls that call attention to themselves because they are not calibrated and working well will be soon be disabled.

Switching vs. Dimming

The choice of dimming versus switching can have major first-cost implications, especially in retrofit situations since the cost of dimming (or controllable) ballasts are about twice that of equivalent non-dimming ballasts.

Switching

Switching systems may be designed to turn off one or more lamps in a multilamp luminaire. This can be achieved with tandem wiring and multiple ballasts, or with multistep ballasts. Multistep ballasts are used to "step-dim" lamps in a luminaire. This eliminates an uneven appearance by reducing the light level of all lamps without switching any off. Switching hardware is relatively simple and generally very cost effective. Switching is always appropriate in singly occupied spaces when light level changes are caused by that occupant (such when an occupant uses a switch or when her lights are switched on by an occupancy sensor). In multiple-occupant spaces, switching must be used with care. An automatic control that causes unexpected changes in light level while a space is occupied may confuse or annoy occupants.

Thus, switching systems that automatically change lights according to a photocell should only be used in spaces where the daylight levels are very high through most of the day. In this case, lights will be off during most of the day, and occupants will not be bothered by cycling. Switching may also be acceptable when occupants are transient or performing non-critical tasks. Switching systems are often appropriate for atria, corridors, entryways, warehouses and transit centers, especially when there is abundant daylight.

- *Potential effects on lamp life.* Because automatic controls may switch lighting loads ON and OFF more frequently than systems with manual control, it's possible that these systems may affect the longevity of the lamps or the relays used to control the lighting. More frequent switching can increase, but usually decreases, lamp life. The effect of increased switching on fluorescent lamp life continues to be an issue that attracts attention (see, for example: Lighting Research Center 1998; Carriere and Rea 1988; Davis, Ji et al. 1996; Ji, Davis et al. 1997; Ji, Davis et al. 1999; Narendran, Yin, et al. 2000; Rundquist, McDougal, et al. 1996).
- *“Calendar life” versus “lamp life.”* When automatic control systems turn off lights, they reduce the number of hours the lamps are burning on any particular day, so they extend the expected lamp life (rated in hours of burn time) over a longer calendar time period. If switching patterns greatly reduce operating hours with only small reductions in lamp life, there may be a net gain in this “calendar life” for the lighting system. (For example, if an occupancy control reduces lamp use from 12 hours to only 3 hours per day, it will produce a net increase in calendar life even if it may have reduced lamp life from 20,000 hours to 15,000 hours.) However, as control systems switch lamps more frequently and lamp life is shortened dramatically, the net “calendar life” will decrease. So there are tradeoffs between lamp life and calendar life that depend on the switching frequency and are different for each lamp and ballast combination. Calendar life should be used to determine relamping schedules; so it affects the resultant maintenance costs as it increases or decreases. There are economic benefits to frequent switching even after the point where calendar life starts to reduce because energy costs continue to decrease with reduced hours of use (more frequent switching). Both energy savings and maintenance costs must be compared to determine the optimum switching frequency.

- *Potential effects on energy savings*. Part of the attention on lamp life is due to the general misconception that any decrease in lamp life is economically unacceptable. In the majority of cases, any small penalty of reduced lamp life is more than offset by the larger economic benefit of reduced energy costs. Because energy costs are the largest component of operating and maintaining a building lighting system, the potential increase in relamping costs that results from increased switching is very small compared to the resultant energy cost savings from the control system.

EPRI Controls Pattern Book (Rundquist, McDougal et al. 1996) presents an economic analysis of the trade-offs between increased relamping costs and decreased energy use for a rapid-start ballasted system. Figure 8-1 shows this analysis for five assumed switching scenarios compared to a base case in which lamps are switched on only once a day. The study concludes that energy cost reductions overshadow relamping cost increases by 6 to over 20 times.

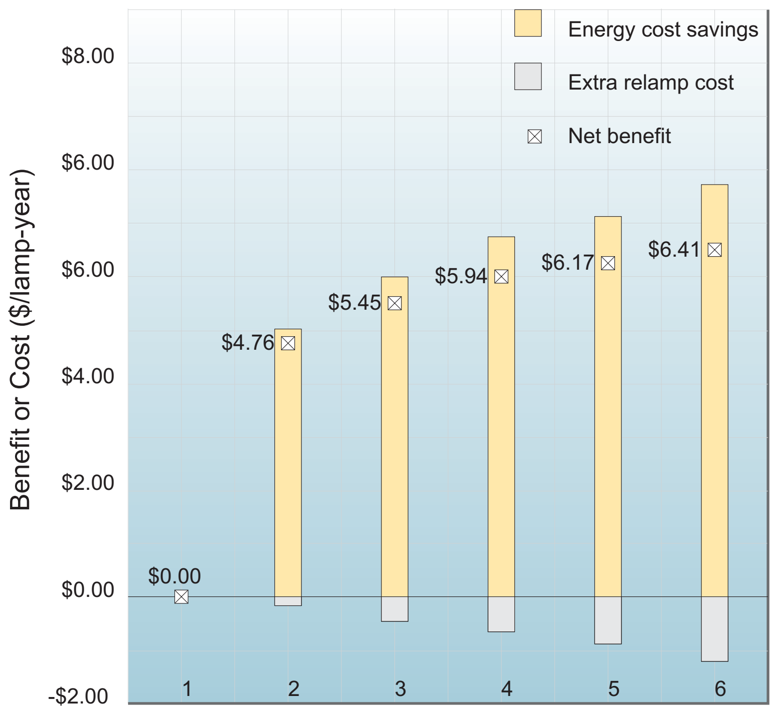


Figure 8-1 – Relamping Costs vs. Energy Use

Effect of switching scenario on extra relamp costs, energy cost savings and net operating cost. The switching scenarios vary from the base case (10 hours per start) to scenario 6 (0.15 hours per start).

Recent studies (Ji, Davis et al. 1997) have shown that the number of switching cycles from rapid-start fluorescent lighting systems is a function of the R_H/R_C ratio (the R_H/R_C ratio is the ratio between the hot lamp electrode resistance and the cold lamp electrode resistance). The R_H/R_C ratio applies to lamp-ballast systems that use rapid-start lamps, including controlled rapid-start, modified rapid start and programmed start. Although the R_H/R_C ratio is finding increased usage, it has not yet been incorporated as a technical specification for most commercial ballasts. For instant-start systems, the R_H/R_C ratio is not applicable since these systems do not apply external electrode heating.

Figure 8-2 gives an idea of the range of switching cycles that could be expected from seven combinations of lamp and ballast.

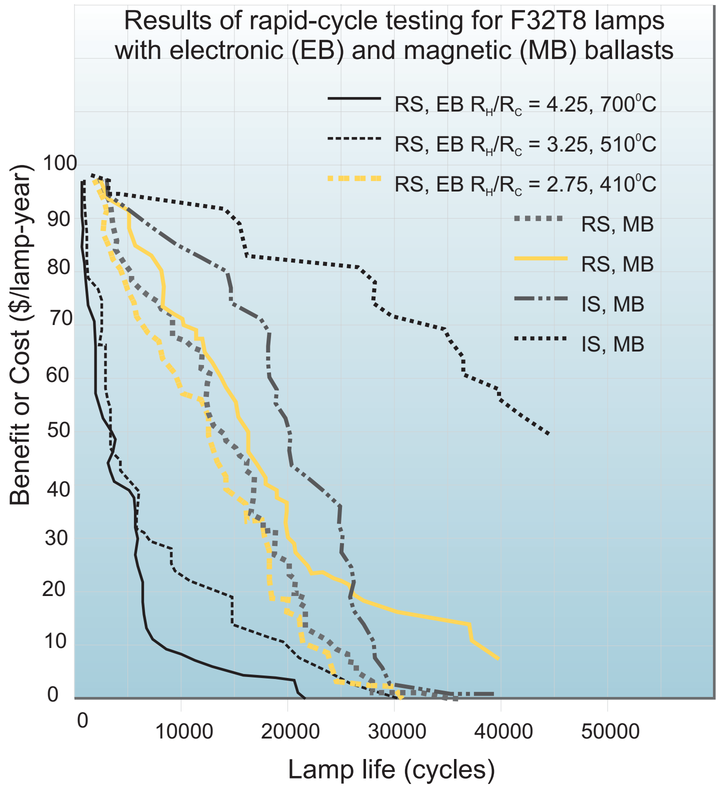


Figure 8-2 – Lamp Switching Cycle Ranges
Shows number of lamp switching cycles for seven different combinations of ballast and F32T8 lamp.
Source: Ji, Davis et al. 1997.

Most studies used the same type of lamp on different ballasts and have shown that lamp life differed according to individual ballast type. In other words, each case is special and there is currently no way to determine lamp and ballast compatibility without taking actual measurements on individual lamp and ballast combinations.

Some combinations of lamp and ballast may result in unacceptably premature lamp failure if the use of controls results in very frequent switching of the lights. Many switching controls, like occupancy sensors, have variable delay times that can be adjusted to minimize excessive switching. *For example, unacceptably short lamp life due to increased switching with occupancy sensors can almost always be corrected in the field by adjusting the occupancy sensors' time delay to 10 minutes or greater.*

- *Inrush current.* When first switched ON, most lighting loads draw several times their steady state current level for the first couple of line power cycles. With some electronic fluorescent ballasts, especially those using active filters in the ballast "front-end" to reduce harmonic distortion, the inrush current can potentially cause the contacts in lighting relays to fuse. If electronic ballasts with active front-end circuitry are switched together in large blocks, it is important to size any lighting relays accordingly. Consult the ballast manufacturer for guidance in specifying relay ratings.
- *Minimum load requirements.* Some sensors, for example "two-wire," wallbox-mounted occupancy sensors, may have minimum load requirements. For the sensor to operate properly, the controlled load must be greater than the minimum required.

- *Switching controls with HID lighting*. Automatic switching controls should generally not be used with high-intensity discharge (HID) lamps except in a few specific circumstances. Since HID lamps have extended warm-up periods and can take several minutes to restrike after having been extinguished, automated controls which frequently switch lights on and off are impractical for these sources.
- A few manufacturers of HID equipment, however, offer two-level HID systems (also called bilevel, stepped ballasts or hi-lo) specifically designed to be used with switching controls like occupancy detectors and daylight switching. In an occupancy sensor application, the low light level is provided when no occupancy is detected. When the occupancy detector senses motion, it triggers the lighting system to go to the high level. Since the lamps are already warm, the transition from low to full light output is very quick. These two-level systems may be quite useful in warehouse aisles, prisons, gymnasiums, and other interior applications where a low light level is desirable even when the space is unoccupied. In addition, hi-lo operation controlled by occupancy sensors may be appropriate for lighting in parking structures. See section 6.6 for a discussion of HID sources, and chapter 7 for information about HID luminaires.

Switching is discussed in more detail in section 8.2.

Dimming

Dimming systems gradually reduce power and light output over a specified range. Since dimming controls alter light levels gradually, they are more likely to be acceptable to building occupants, especially those working at stationary tasks. However, dimming hardware is more expensive than switching and the commissioning process is more elaborate. Dimming is described briefly below and in more detail in section 8.2.

Special dimming ballasts are required for fluorescent and HID lamps, which increases their cost considerably. Several manufacturers have adopted a standard 0–10 V dimming protocol that allows ballasts from different manufacturers to be used with compatible controllers, also from different manufacturers. Other systems are proprietary, requiring that the ballast and control module be from the same manufacturer. Sections 6.5 and 6.6 discuss fluorescent and HID dimming ballasts, respectively.

In general, fluorescent dimming ballasts fall into two categories: (1) energy conservation products with a range from 100% down to 5–10% light output, and (2) architectural dimming products with a range from 100% down to <1% light output. Architectural dimming ballasts are significantly more expensive and are not necessary for energy conservation. They should only be specified where very low light levels are required for a task or for an aesthetic purpose.

Unlike incandescent lamps, dimming does not extend lamp life for fluorescent and HID lamps; in fact, long periods at minimum light output may reduce lamp life. Metal halide lamps will show strong color shifts with dimming (especially with uncoated lamps), but fluorescents should show only minor color changes.

Some fluorescent dimming ballasts can now switch off after they reach the point of minimum dimming, which may be beneficial for maximum energy efficiency. However, at the time of this writing, these ballasts continue to draw about 6 watts of power (for a 2-lamp ballast) after they are switched “off.” This continued energy use must be accounted for in savings estimates. An important feature of these systems is the ability to switch lamps back on at the dimmed level.

Some dimming electronic ballasts are individually "addressable," allowing them to be assigned to a control group after installation. These ballasts transmit their individual digitally encoded identification number to a special IR (infrared) remote or wallbox controller, which then assigns them to a control group and communicates the group's dimming or ON/OFF instructions. If task areas or daylight availability changes, they can easily be reassigned to another group without rewiring.

A key characteristic of a dimming system is the relationship between the light output of the electric lighting system and the input power. This is shown in Figure 8-3 for a typical dimming fluorescent and HID system. While a fluorescent dimming system has a slight loss in efficacy at lower light levels, an

HID dimming system has a significant loss in efficacy. A switching system, on the other hand, involves no change in efficacy, and 100% energy savings when a lamp is turned off.

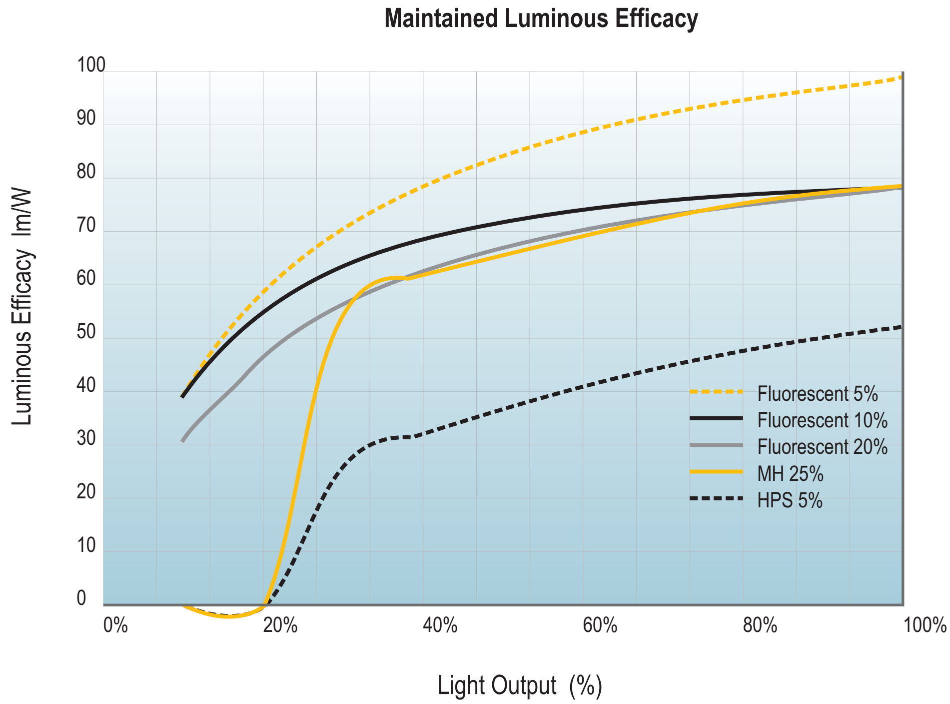


Figure 8-3 – Dimming Efficacy Characteristics for Fluorescent and HID Systems
Graphic courtesy Heschong Mahone Group.

Multilevel (Hi-Lo) Ballasts

Hi-lo and multilevel ballasts are specially designed ballasts that can operate lamps at two or more light output steps. Like switching systems, they usually produce abrupt light level changes, although some systems incorporate a timed fade rate that causes a more gradual change. Since these systems only have to produce a few discrete light levels, the ballast manufacturer can optimize performance at each. Other things equal, these multilevel systems can provide a few light levels more efficiently than a continuous dimming ballast. Like dimming systems, they are always drawing power and run at reduced efficiency at their lower settings. Hi-lo are less expensive than equivalent dimming ballasts.

The most common application for multilevel systems is for metal halide lamps in high-bay applications where two light levels can be selected for high or low daylight conditions. (Luminaire selection for high-bay applications is discussed in section 7.5.2.) Fluorescent hi-lo ballasts are also available, and have been used in libraries, retail spaces, and other public buildings. Fluorescent hi-lo photocontrol systems may offer opportunities to be combined with daylight adaptation strategies (see Adaptive Compensation, section 8.6.1).

The use of multilevel HID lamp ballasts is one way to solve the "hot restrike" problem that complicates the use of HID lamps with controls. When an HID lamp is switched off, it has to cool before it can be restarted. For some lamps, this “re-strike” period can be as long as 20 minutes (see discussion of HID lamps in section 6.6). However, when an HID lamp is powered down to a low light-output level, it can resume full light output within seconds. Thus, multilevel HID ballasts allow HID lamps to switch from low to high state in matter of a few seconds, with the complete change taking about a minute. Several manufacturers now offer these products.

A key characteristic of a multilevel lighting system is the relationship between the light output and the input power. This is shown in Figure 8-4 for several typical multilevel systems.

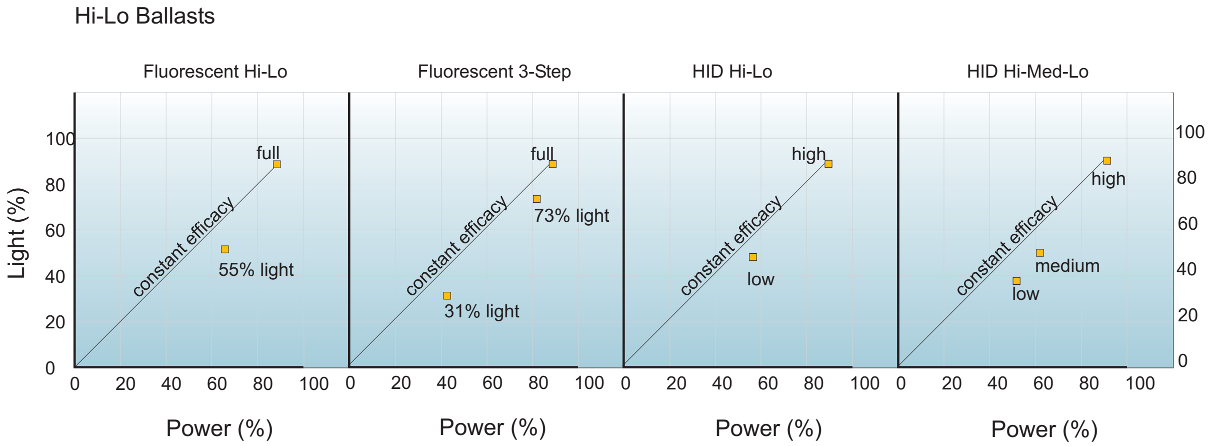


Figure 8-4 – Light Output and Input Power for Hi-Lo Fluorescent and HID Ballast Systems
Graphic courtesy Heschong Mahone Group.

8.1.4 Energy Savings

Lighting controls reduce building operation costs. Properly operated lighting controls reduce lighting energy when lighting is unnecessary and reduce lighting demand when and where possible. Energy use consists of two components: power, which is the rate of electricity consumption, and time, which is the period of consumption. This is expressed as:

$$\text{Energy} = \text{Power} \times \text{Time}$$

Equation 8-1

Effective lighting controls reduce both power and time.

Occupancy sensors reduce the time of lighting operation. Time switches and programmable relay systems also reduce hours. Dimming controls, such as daylighting, reduce or eliminate lighting power throughout the day even in occupied areas. Reducing energy use during peak periods may also reduce lighting demand and related peak demand charges.

Determining the energy savings potential of any lighting control device or system is an inexact science. Unlike a more efficient piece of equipment (such as replacing a magnetic ballast with an electronic ballast), lighting controls only save energy if they are properly applied and used to reduce lighting hours and/or power. In other words, lighting control savings depend on *how* they are used, and savings are relative to how energy was used prior to installation of the controls.

Since every building is different, it is difficult to know how much energy lighting controls are likely to save in any given application. In large part, the energy savings from controls depends on how the building lighting was operated before the controls were installed. If building occupants are conscientious with lighting, then energy savings would be modest. However, many buildings enclose spaces where automatic controls can significantly reduce wasted lighting energy by eliminating lighting during unoccupied times or reducing electric light levels where adequate daylight is available.

Table 8-4 presents estimates of the maximum yearly energy savings that would be expected per controlled circuit according to control type, space type and typical hours of operation. These estimates are used to project energy savings in the applications presented in chapter 5. Use these numbers with caution since actual energy savings are highly variable in any given building application. In addition, the energy savings values listed are the maximum expected values, not the average, and assume that the control devices are properly specified, installed, commissioned and operated. Savings values are not additive; use of multiple controls may result in lower savings for each individual control.

Table 8-4 – Lighting Control Energy Savings Examples by Application and Control Type

Space Type	Controls Type	Maximum Expected Yearly Energy Savings
Private Office	Occupancy sensor	45%
	Sidelighting w/photosensor	35%
	Manual dimming or multilevel switching	30%
Open Office	Sidelighting w/photosensor	40%
	Occupancy sensor	35%
Classroom	Multilevel switching	15%
	Sidelighting w/photosensor	40%
	Occupancy sensor	25%
Grocery Store	Adaptive compensation	15%
	Toplighting w/photosensor	40%
Big Box Retail	Toplighting w/photosensor	60%
	Bilevel switching	10%

8.1.5 Responding to Emergency Alerts

The biggest economic driver for peak demand reduction is the instantaneous cost of electric energy. As electric utility industry restructuring takes place, the utilities' high cost of producing energy during peak times is increasingly being passed on to the ratepayer. The need for building managers to reduce lighting demand during peak periods will increase. During periods of electric power unreliability, the ability to curtail electric power may mean the difference between continued operation or having to shut down because of rolling power outages. (See section 3.1.4 for a more detailed discussion of lighting impacts on peak electric load.)

Reducing electric power usage during emergency alerts can be implemented either automatically by building managers and/or in coordination with building occupants. E-mail is an increasingly effective tool for urging workers to reduce non-critical electric loads, such as computer monitors, other office equipment, or task lights. Reducing peak lighting loads also reduces the HVAC load since less heat is added to the conditioned space.

Reducing lighting automatically is a more extreme reaction to emergency alerts, but in some cases can be economically justified. For example, dimming the lighting system can be justified if electric energy costs are momentarily very high or if the likelihood of a power outage can be reduced. Power outages can be very expensive in commercial buildings, especially in the retail sector. In general, automatic reductions in light level should not be done before voluntary measures are exhausted. One opportunity for energy service providers is to provide software that takes into account the local utility

Using Dimmable Lighting to Respond to Momentary Energy Price Increases

Since most buildings use dimmable lighting only for a small portion of the lighted floor space, the potential for treating lighting as a sheddable load for accommodating momentary energy price spikes is limited. Most buildings cannot operate if the building lighting is switched off. However, if building lighting systems were dimmable, then a significant fraction of the building's electric load could be instantaneously lowered to respond to a rapid price increase. Although light levels would be reduced at the same time, this would clearly be a preferable alternative to sending employees home because of a major power outage.

Sheddable lighting requires both the use of dimming equipment as well as the necessary automation to assure that the building lighting responds to changing energy prices quickly and efficiently. There is a cost associated with this additional equipment as well as commissioning costs, and there are few companies that offer these services at the time of this writing.

rate structure to provide continually updated energy costs that building managers can respond to. (See 8.5.4 for more information about building-integrated controls for load shedding.)

8.1.6 Commissioning

Commissioning is defined as “a systematic process of ensuring that all building systems perform interactively according to documented design intent and the owner’s operational needs” (Portland Energy Conservation 1992). In a total building project, commissioning is a team effort involving the commissioning agent, owner, designer, engineers, contractors, facility manager and building operating staff.

In practice, lighting controls don't always realize their full energy savings potential. This is often due to inadequate commissioning and calibration during or after installation. This section discusses the importance of commissioning lighting controls and presents some practical advice for effective calibration.

Importance of Commissioning

California's Title 24 (Energy Efficiency Standards for Residential and Nonresidential Buildings) requires that in new nonresidential buildings, lighting zones not equipped with occupancy sensors must be automatically switched off (“swept off”) after normal working hours. For a computer-based “sweep-off” system to reduce energy usage as intended by code, someone must ensure that the desired “off” times for each controlled zone in the newly installed system have been entered into the computer program that controls the lighting system operation. Without this step, the lights may not be swept off automatically at all. The failure to commission the control system in this example could result in even greater energy use than a system with no controls at all.

In many lighting projects, particularly retrofits in existing commercial buildings, there may be no commissioning agent. This is a serious problem because most lighting systems will not perform according to design intent without commissioning.

Calibration

Calibration is a subset of commissioning. It refers to an electrical or mechanical adjustment to a sensor to obtain the desired output from the sensor given the actual range of the physical parameter input, such as light or the heat patterns from moving warm bodies. In older systems, the actual calibration adjustment is usually accomplished by physically turning a set screw in a sensor or on the controller. In more sophisticated systems, calibration may be accomplished using a software interface.

Most sensors require calibration because it is not known a priori what range of inputs may be encountered in any particular building application. Consider, for example, two adjacent daylit office spaces, one with dark, the other with light furnishings. Even if all the other physical conditions, such as the window size and orientation, are the same, one would expect light sensors in these two spaces to read significantly different values. In particular, the quantity of available daylight striking the sensor is likely to exhibit extreme ranges (from 0–100,000 lux), especially if the window treatment does not entirely exclude direct sunlight.

Commissioning Checklist

Because there are so many ways to configure lighting control systems, the specific details of calibration and commissioning will vary from system to system. The calibration and commissioning activities required for most modern lighting control systems are described in Table 8-5.

Table 8-5 – Calibration and Commissioning for Different Control Types

Control Type	Calibration and Commissioning Activities
All	Verify correct sensor placement and orientation per construction drawings and/or specifications. If unanticipated obstructions are present, adjust sensor location and field of view for optimum operation.
Dimming systems	Burn in new lamps by operating at full power continuously for 100 hours.
Daylight-linked	Be sure all furnishings and interior surface materials are installed before calibration. Make required calibration adjustment(s) at the light sensor or controller to obtain desired light level at the work surface. This may require calibrations be performed under two conditions: at dusk (to simulate low daylight conditions) and during the day under bright daylight conditions. If window coverings can be controlled, dusk condition can be approximated by closing all window blinds or other window coverings. If possible, record the position of the calibration adjustments for one space and then replicate the settings on similar spaces.
Occupancy sensors	Verify correct sensor placement and orientation (if applicable) per construction drawings and/or specifications. Adjust the sensitivity and time delay of the occupancy sensor. Test for appropriate response.
Sweep-off	Input the schedule for lighting system operation into the programmable controls. Input appropriate start and stop times to accommodate weekday, weekend and holiday operation. Verify correct operation of overrides. Properly located overrides MUST be provided.
Manual dimming	Verify that the dimmer has been installed in correct position adjacent to the wall switch per drawings. If applicable, set upper limit of dimming range appropriate to the task being performed. If applicable, set lower limit of dimming range so that no lamps flicker.
After commissioning	Inform occupant(s) about the functionality of the controls and, particularly, the overrides. Provide building maintenance personnel with all necessary documentation and operating instructions to re-commission and maintain the system.

State of Current Commissioning Practice

Few electrical contractors have experience with commissioning lighting control systems. This lack of expertise is a serious barrier to the widespread adoption of lighting controls by the building industry. To overcome this barrier, contractors must develop the skills to properly commission the controls as part of the installation. Also, commissioning should be made a requirement in the contract documents so that the additional costs can be included in the overall bid.

To assist contractors, manufacturers should make products that can be easily and quickly commissioned, and should include clear, step-by-step instructions for calibrating and commissioning their products, both as components and as building systems. Further manufacturer assistance, including contractor training and certification, or being present on-site when the contractor commissions the system and providing the contractor with any necessary specialized equipment (such as light meters) on a short-term basis, may be required to assure proper system functioning.

8.1.7 Maintenance

All control systems need periodic maintenance and confirmation that they are still working correctly. For example, occupancy sensors may be blocked by a new furniture arrangement, or light sensors may need to be re-adjusted if a new building just went up next door, redirecting daylight. At least once a year, maintenance personnel should inspect the lighting controls and verify proper operation of all control devices. Photoelectric controls, whether switching or dimming, require occasional cleaning of the photosensitive surface. The frequency of cleaning depends primarily on the cleanliness of the environment. Photoswitches that are externally located or photocells that are mounted in dirtier locations such as skylight wells may require cleaning every six months.

Relay-based scheduling systems need occasional checking. Some zones may end up being permanently overridden. In this case, the cause of the overrides should be determined before simply clearing the override setting. The relay(s) may have been overridden in response to a problem that has not been fixed.

Well-designed control systems can also reduce lighting maintenance costs. Occupancy sensors may actually increase the calendar life of fluorescent lamps, thus effectively increasing the relamping interval. Some systems also provide indicators of accumulated operating hours that can be used by maintenance personnel to best schedule group relamping intervals. By reducing the need for spot-relamping, labor costs can be saved or used more effectively for other maintenance purposes.

8.2 Switches and Dimmers

8.2.1 Description

Personal lighting controls refers to switches and dimming systems that provide building occupants with a high degree of control over their local lighting. The trend toward using personal controls is helping property managers to address a longstanding problem: the difficulty of knowing in advance what visual tasks will be performed in different areas, when these tasks will be performed, and what light levels are required.

Personal controls fall into two broad categories: switches and dimmers. This section discusses on/off switches, bilevel switching and personal dimming controls.

Multilevel Switching

With proper wiring, it’s possible to provide different light levels from the ceiling lighting system. Multilevel lighting is achieved either by switching groups of luminaires or selectively wiring multiballasted luminaires so that multiple light levels are provided at the luminaire level. Some building codes require multiple lighting level control in all individually controlled rooms. Often, this requirement is fulfilled using bilevel switching. With bilevel switching, room occupants are provided with two wall switches near the doorway to control their lights. In a typical installation using three-lamp luminaires, one switch would control one-third of the fluorescent lamps in the ceiling lighting system (the inboard lamps), while the other switch would control the remaining two-thirds of the lamps (the outboard lamps). This allows four possible light levels: OFF, 1/3, 2/3 and FULL lighting. In an installation using two- or four-lamp luminaires, only three light levels would be possible: OFF, 1/2 and FULL lighting.

Figure 8-5 shows an example of bilevel switching with tandem wiring (ballasts controlling lamps in adjacent luminaires) for a typical office application with both 3-lamp and 2-lamp luminaires. Note that in the room with 2-lamp luminaires, only 1/2 and full lighting can be provided with bilevel switching, while the room with 3-lamp luminaires allows an extra step in light level.

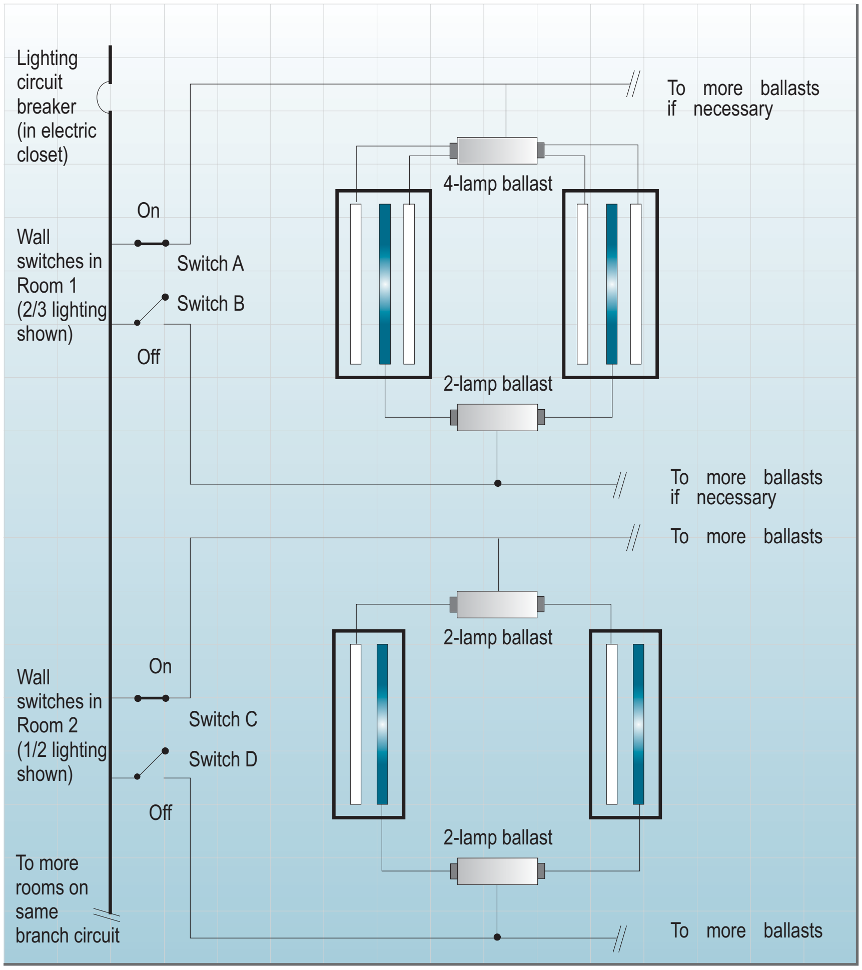


Figure 8-5 – Bilevel Switching in Typical Office Application

Bilevel switching is simple and durable. Specifiers and electrical contractors are familiar with this improved wiring system and it requires no special maintenance or user training to retain its functionality. While the energy savings may not be optimum, bilevel switches are likely to remain useful for the full life of the building wiring. Furthermore, by installing bilevel switching now, a building can be inexpensively retrofitted later with intelligent lighting communications technologies that will become available in the future.

Bilevel Switching in the San Francisco Federal Building

Building office occupants often turn on lights using just one switch rather than both when entering the room. In a study of 30 daylit perimeter offices (see description of the study in section 8.3.6), it was found that the occupants elected to set their lights at less than full lighting *45% of the time.* In fact, 28% of the time, the occupants only used 1/3 of the available lighting, saving significant amounts of lighting energy.

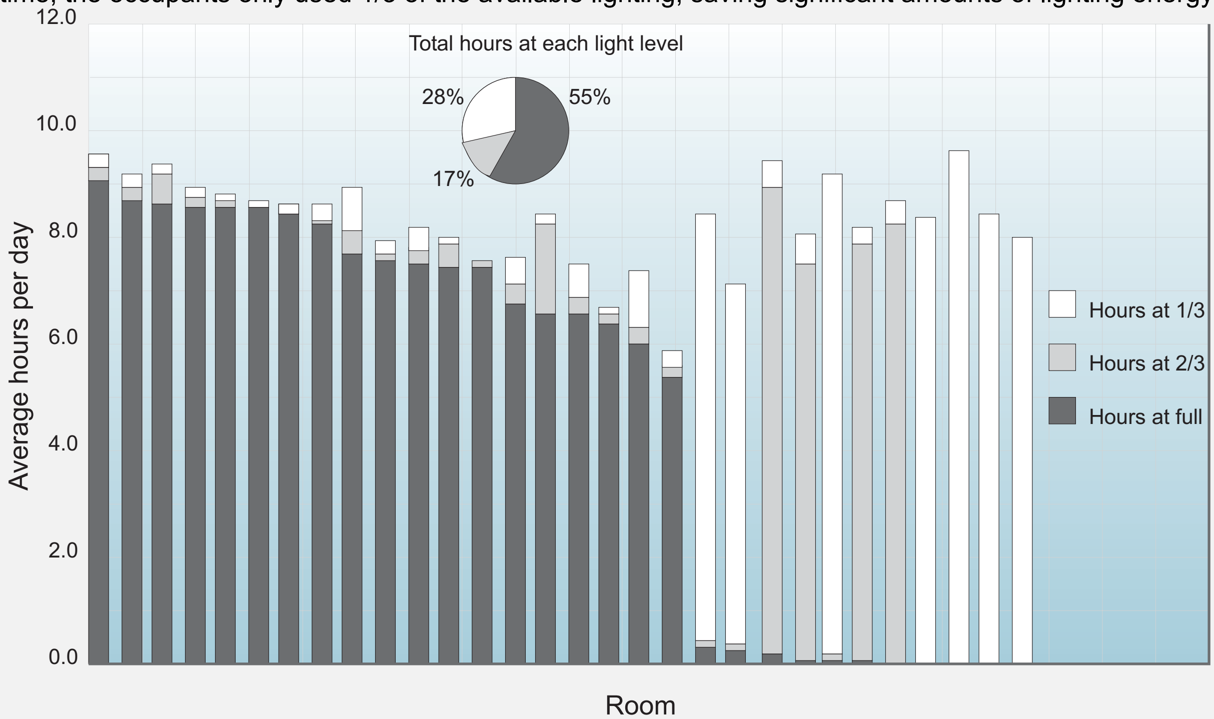


Figure 8-6 – Bilevel Switching Use

The occupants set lights at less than full lighting 45% of the time, and they used 1/3 lighting 28% of the time, saving significant amounts of lighting energy (24%). Source: Jennings, Rubinstein et al. 2000.

8.2.2 Manual Dimming

Manual dimming provides building occupants with a high degree of control over their overhead lighting, thereby easily accommodating changing lighting needs.

Manual dimming controls are usually implemented as:

- *Manual wall-mounted dimmers.* These dimmers are usually located in switch wallboxes near the area that is controlled. Many styles are available, from functional to decorative.
- *Remote dimmers.* These dimmers may consist of a knob or slider in easy of reach of the occupant. Several manufacturers now offer portable (TV-style) remote controls that allow occupants to dim their lights from anywhere in a room.

In the near future, lighting systems will increasingly be controllable from personal computers and personal digital assistants (PDAs). Several companies now produce lighting products that can be controlled using virtual control panels on computer desktops.

Dimmer Location Considerations

The dimming control's location and its integration with the on-off switch should be considered when specifying manual dimming controls. The location of the control, whether it is mounted on the wall near the entrance or as a knob on the desktop, may affect whether the dimmer is used frequently or rarely. The more convenient to the occupant, the more likely it is to be used.

Control Setup (Configuration)

Although manual dimming provides occupants with a high degree of control over their lighting, it is best to provide a manual switch as well as the dimmer. Most dimming systems don't allow the lamps to be entirely extinguished. If a manual switch is not provided, then the room lighting will always be on. This will result in wasted lighting energy and may also give the appearance that the room is occupied when it is not.

The best solution is to provide a modern manual slide dimmer (slider) with an integral on-off switch in the wallbox near the space's entryway (see Figure 8-7).

Dimming Usage in the NCAR Building

In a field study at the National Center for Atmospheric Research (NCAR) building, dimming usage behavior was analyzed both from the energy usage data and by surveying the occupants. The power usage data indicated that occupants used a desktop dimmer two to three times as often as a dimmer not located near the desk (that is, wall mounted). This suggests that the dimmer location should be carefully considered when specifying manual dimming controls. These findings were confirmed in the user surveys, where 60% of the occupants polled indicated a preference for the dimmer to be located close to their workstation. Only 11% of the occupants preferred the dimmer to be located near the door.

Do people value personal lighting controls? When asked why they adjusted their lights using manual dimmers, about 50% of the occupants who responded to the questionnaire indicated that they adjusted their lighting for computer work, 23% adjusted their lights for daylight, 15% for reading printed material, and 12% for atmosphere. These results suggest that the now ubiquitous presence of computer screens in the work environment is a major driver for occupants to use personal dimming.

See section 8.3.6 for more about the NCAR study.

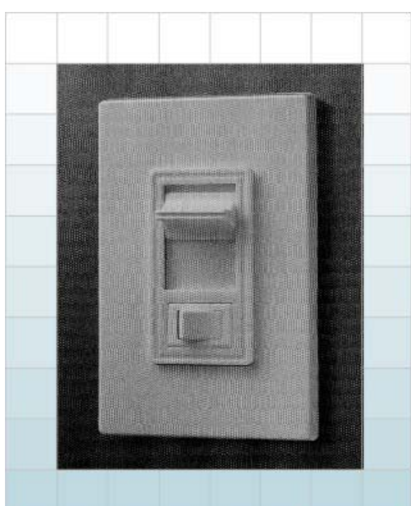


Figure 8-7 – Control Device Combining Manual Dimmer and Wall Switch
The device must be compatible with the connected lighting load. Photo courtesy Hunt Controls.

8.3 Occupancy Sensors

Occupancy sensors are switching devices that respond to the presence and absence of people in the sensor's field of view. The occupancy sensor system is usually made up of one or more components, which include a motion detector and a control unit consisting of a transformer for power supply and a relay for load switching. The sensor sends a signal to the control unit that switches lights on and off. Most sensors include manual and/or automatic controls to adjust sensitivity to motion and to provide a time delay for shut-off of lights upon vacancy.

The motion detector uses either ultrasonic sound waves or infrared radiation technologies for sensing motion. The electronic control unit collects the information supplied from the sensor(s) and determines the occupancy status of the space using a built-in control algorithm. Most occupancy sensors allow the control unit to be calibrated to adjust the sensitivity of the sensor to motion. The controller also incorporates a programmable timing device that will turn off the lights after the room is unoccupied for a specific period of time (this is also usually adjustable). Output from the control unit either energizes or de-energizes the relay, which opens or closes the circuit serving the luminaires. Relay contacts must be properly sized to handle the line voltage and current.

The sensor's power supply transforms the 120 or 277 AC line voltage for powering the control unit's circuit (usually 24 VAC) and for sending output to the relay. The relationship between the power supply, relay, controller and motion detector is shown in Figure 8-8.

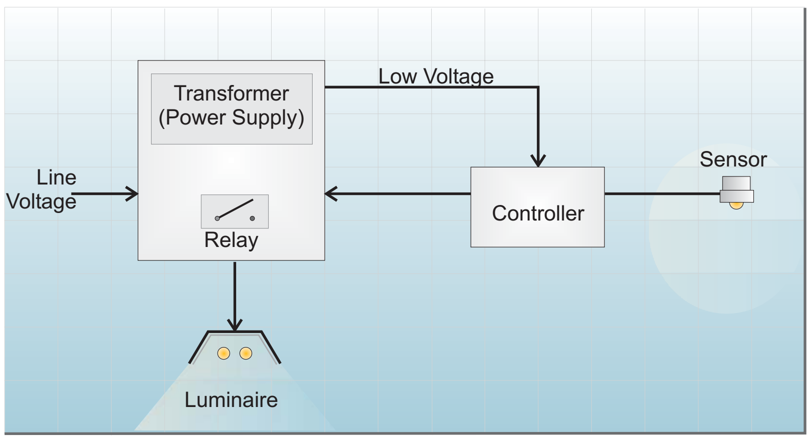


Figure 8-8 – Occupancy-sensor Control System

In most occupancy-sensor systems, the motion detector and controller are housed in one package located in the controlled space. The power supply and relay comprise another unit, sometimes called a powerpack or switchpack. It's often convenient to locate the switchpack at the junction box serving the appropriate circuit leg. Separating the sensor location from the switchpack provides effective control while minimizing high voltage wiring costs. In wallbox sensors, components are integrated into one compact package, designed to fit into an existing switch box. The solid-state switches often used in these wallbox packages are rated for relatively small loads.

Occupancy sensors can also be connected to low-voltage relay and building automation systems. If the sensor is connected to a low-voltage relay system, the low-voltage operating power is derived from the relay panel's low-voltage supply.

8.3.1 Types of Occupancy Sensors

The most common methods to detect motion are ultrasonic or passive infrared (PIR) detection. Most modern occupancy detectors use either one or both of these methods to detect occupancy reliably. In addition, some sensors combine ultrasonic or PIR detection with another sensing mechanism, such as sonic detection, as an additional clue to space occupancy or vacancy.

Ultrasonic (US)

Ultrasonic occupancy sensors activate a quartz crystal that emits ultrasonic waves throughout the space. The unit then senses the frequency of the reflected waves. If there is motion, the reflected wave's frequency will shift slightly. This change in the ultrasonic waves frequency is called the Doppler effect and is detected as motion in the space. Ultrasonic sensors operate at frequencies higher than the normal human ear can detect (about 20kHz). To avoid possible incompatibility with other devices (such as hearing aids), most modern ultrasonic sensors operate at frequencies 32 kHz or higher.

Figure 8-9 shows the detection pattern of an ultrasonic sensor. The ultrasonic sound waves cover the entire area in a continuous fashion—there are no blind spots or gaps in the coverage pattern. They can also detect movement behind some barriers. For this reason, ultrasonic sensors may be more effective in detecting occupancy than PIR-based detectors. For example, hand motion can be detected at a distance of about 25 ft, arm and body torso detected out to 30 ft and full-body motion can be detected out to over 40 ft. The sensitivity range of different products will vary significantly.

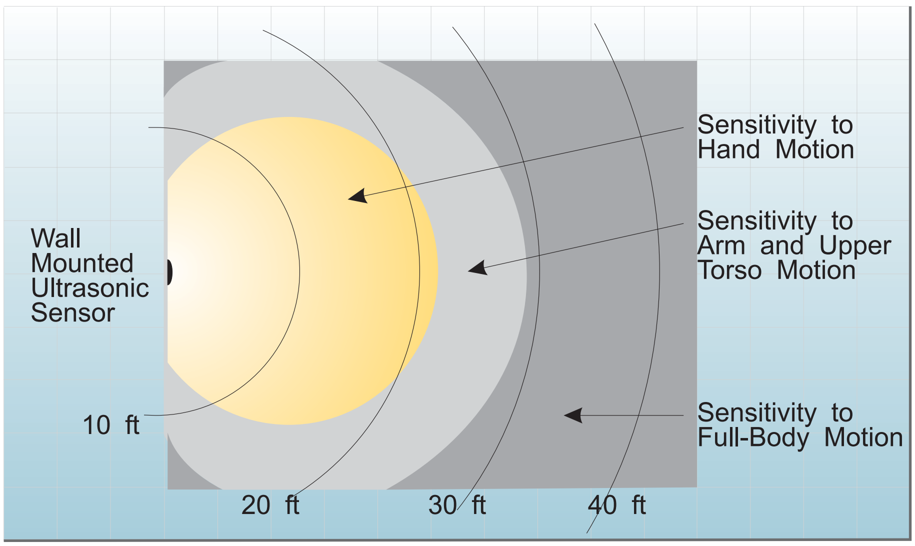


Figure 8-9 – Typical Sensitivity Pattern for Wall-mounted Ultrasonic Sensor
Source: Proceedings of the North Texas Association of Energy Engineers, May 13-14, 1991

Ultrasonic sensors are more sensitive to false ONs than PIR detectors. A false ON occurs when an occupancy detector switches on lighting when the space is not occupied. False ONs are caused by motion in adjacent spaces, by air turbulence near air diffusers and open windows, and by hanging objects in the space. Most ultrasonic sensors work best in spaces with ceilings below 14 ft but there are some that can detect a moving person from a height of 30 ft or more.

Passive Infrared (PIR)

Passive infrared (PIR) sensors react to the infrared heat energy emitted by people. PIR sensors are passive devices in that they only detect radiation; they do not emit it. They are most sensitive to moving objects that emit heat energy at a wavelength of around 10 microns (the peak wavelength of the heat energy emitted by humans). PIR sensors are strictly line-of-sight devices. They cannot "see" around corners and a person will not be detected if there is an obstruction, such as a partition, between the person and the detector.

PIR sensors employ a pyroelectric transducer to detect infrared radiation. The device converts the IR energy into a voltage signal. A many faceted lens surrounds the transducer and focuses heat energy onto the detector. The lens views the area with a multitude of narrow and discrete beams or cones. As such, it does not view the area in a continuous fashion. As an occupant moves a hand, arm or torso from one cone of vision to another, a positive signal is generated and sent to the controller.

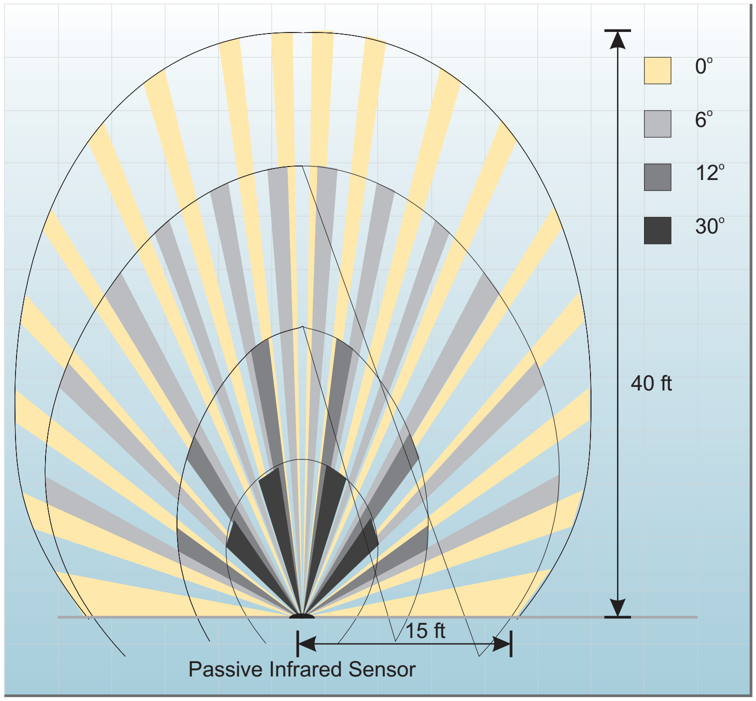


Figure 8-10 – Typical Coverage of Passive Infrared Sensor
Shown in plan view. Degree labels indicate angular extent of fan pattern in section.
Courtesy The WattStopper.

The detection pattern of PIR sensors is fan shaped, forming "fingers" of detection. Each finger is a cone of heat detection "seen" by a segment of the detector's faceted lens. As shown in Figure 8-10, there are gaps of coverage between adjacent fingers. These gaps widen with distance. At 40 ft from the sensor, for instance, the coverage gap may be as much as 8 ft. Since the sensor is most sensitive to motion that moves from one sensing cone to another, its sensitivity decreases with distance as the gaps between sensing cones widen. Most PIR sensors are sensitive to hand movement up to a distance of about 15 ft, arm and upper torso movement up to 20 ft, and full-body movement up to about 40 ft. The sensitivity range of PIR sensors can vary substantially, however, depending on product quality and electronic circuiting design.

PIR sensors are less susceptible to false ONs than ultrasonic sensors. In addition they are better in applications where it's desirable to detect occupancy in only a portion of a space. PIR detectors can be effective in spaces with ceilings up to 20 ft or more.

Acoustic

Although there are too many sources of sound in the working environment for acoustic detection alone to detect occupancy reliably, acoustic detection can be combined with PIR detection to detect occupancy reliably.

Dual Technology

Most manufacturers offer dual-technology occupancy sensors that use both ultrasonic and PIR for detecting occupancy. Dual-technology sensors usually require that both the ultrasonic and PIR detectors sense occupancy before switching lights ON, making them relatively immune to false ONs. Once a space is occupied, the sensor will keep the lights ON if *either* the ultrasonic or PIR detector senses occupancy. This tends to reduce the false OFFs experienced with PIR detection in larger spaces. However, they may continue to keep lights on after a space with heavy airflow is vacated. Some manufacturers have circuitry to reduce this possibility.

Dual-technology sensors are advantageous mainly in large spaces with excessive airflow. They are usually less susceptible to false ONs than ultrasonic only and false OFFs than PIR only. They are generally more expensive than single-technology sensors.

Figure 8-11 provides a flow diagram to help decide whether ultrasonic, PIR or dual-technology occupancy sensors are most appropriate for a particular application.

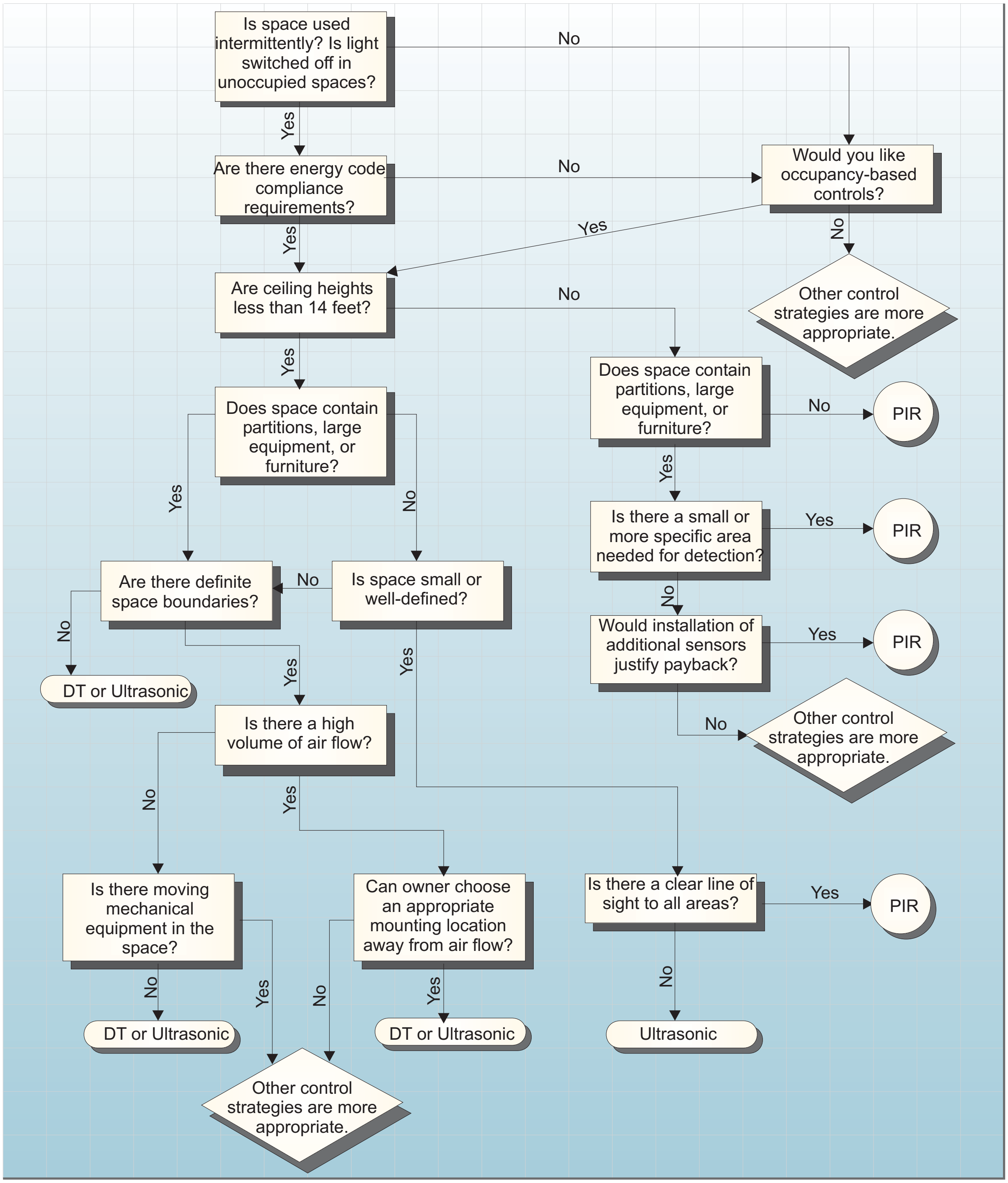


Figure 8-11 – Selecting Occupancy Sensor Types

Flow diagram shows how to select different occupancy sensors types based on the application. Courtesy WattStopper.

8.3.2 Mounting Packages

Occupancy sensors come packaged in one of four ways depending on their intended mounting location.

- *Ceiling mounted*. Mounted in the ceiling of the space where the lights are to be controlled.
- *High wall or corner mounted*. Mounted high on the wall or high in a corner of the space to be controlled.
- *Wallbox mounted*. Mounted in a wallbox, typically next to the doorway leading into the controlled space.
- *Personal or portable*. Located near the workstation or area that they control.

An occupancy sensor's mounting packaging influences its effective range and coverage. Table 8-6 summarizes these characteristics.

Table 8-6 – Typical Occupancy Sensor Performance Characteristics

Mounting Location	Sensor Technology	Angle of Coverage	Typical Effective Range[1]	Optimum Mounting Height
Ceiling	Ultrasonic	360°	500–2000 ft^2	8–12 ft
Ceiling	PIR	360°	300–1000 ft^2	8–30+ ft
Ceiling	Dual PIR/US	360°	300–2000 ft^2	8–12 ft
Wall Switch	Ultrasonic	180°	275–300 ft^2	40–48 in.
Wall Switch	PIR	170–180°	300–1000 ft^2	40–48 in.
Corner Wide View	PIR & dual PIR/US	110–120°	To 40 ft	8–15 ft
Corner Narrow View	Passive Infrared	12°	To 130 ft	8–15 ft
Corridor	Ultrasonic	360°	To 100 ft	8–14 ft
High Mount	Passive Infrared	12–120°	To 100 ft	To 30 ft
High Mount Corner	Various Dual	110–120°	500–1000 ft	8–12 ft
High Mount Ceiling	Various Dual	360°	500–1000 ft	8–12 ft

[1]Sensitivity to minor motion may be substantially less than noted here, depending on environmental factors

Ceiling Mounted

Applications for ceiling-mounted sensors are nearly universal: they may be used for either small or large areas, and they have few limitations.

The typical ceiling-mounted system consists of a motion detector/controller unit connected to a switchpack housing, containing the power supply and relay. Often the switchpack is located in or mounted onto the junction box (j-box) in the ceiling electrical system. Class II (low voltage) wiring is all that is required for communication between the switchpack and the sensor.

The high mounting position of ceiling-mounted sensors allows good coverage of large areas that have obstructions, such as partitions and furniture in open office spaces. Multiple sensors can be networked to cover large areas that exceed the range of a single unit. Ceiling-mounted ultrasonic occupancy sensor devices are available in coverage patterns ranging from about 250–2000 ft^2. Ultrasonic sensors are also available for applications in narrow spaces, such as corridors and warehouse aisles. These can detect occupancy in a space up to 100 ft from the sensor.

High Wall or Corner Mounted

Another packaging configuration for occupancy sensors is high wall or corner mounted. By locating the sensor high on the wall or corner of the space to be controlled, greater coverage is possible than with a wallbox-mounted sensor.

Wallbox Mounted

Wallbox-mounted occupancy sensor units are useful for smaller offices and similar applications where the higher cost ceiling-mounted units may be considered too expensive. Wallbox units have all components in a single housing and can be easily wired into existing switch boxes. There is little design flexibility since the wallbox location is fixed, in most cases, at 42 in. above the floor, and the sensor head may be easily damaged since it is so accessible. Another drawback is that any existing room partitions and furnishings will limit coverage. However, in the appropriate spaces (small offices and open conference rooms that have wall switches) wallbox sensors can be quite cost effective since the devices are relatively inexpensive and the installation cost low.

Wallbox sensors are available in both PIR and ultrasonic technologies. Both ultrasonic and PIR wallbox sensors have a typical effective range of sensitivity to minor motion (such as hand motion) of up to about 300 ft^2. In addition, PIR wallbox sensors may be sensitive to gross motion in areas of up to 750 ft^2. The field of view for wallbox PIR sensors is usually about 120 degrees, but some units are available with a wider range up to 180 degrees. Some sensors can be masked to limit the field of view if desirable.

The maximum load rating for wallbox sensors ranges from 800 to 1000 watts, at 120 volts, and up to 2000 watts with 277-volt service.

Some wallbox sensors do not use "air gap" relays to switch loads ON and OFF. This means that some residual current can continue to flow to the fluorescent ballasts even though the lamps appear off. This may affect the performance of some brands of electronic high-frequency ballasts. The sensor manufacturer can provide the necessary information as to this limitation.

Personal or Portable

Several manufacturers now produce occupancy sensors that are small and portable and are designed to be mounted within a few feet of the occupant. Because these systems are portable, they are appropriate for controlling lighting and other loads in individual cubicles or workstations. Typically this type of sensor will have very limited range since it is intended to operate only in a small area. The sensor itself is a low-voltage device. It is connected using low-voltage wiring to a switchpack (or relay) that actually switches the load on or off. There are several advantages to portable sensors compared to fixed sensors:

- With the occupancy sensor and light sensor located near the occupant, the presence of the occupant can be detected reliably. Also, the illumination level measured by a photocell near the occupant's work surface may give a better indicator of desktop illuminance than a ceiling-mounted photosensor.
- The stalk that holds the sensor can double as a location for manual dimming controls and calibration adjustments.
- Plug loads for the local workstation can be tied to the same controls, allowing broader environmental control for the occupants, and reducing system costs.

8.3.3 Special Features of Occupancy Sensors

Modern occupancy sensors, whether ceiling-mounted or the wallbox type, offer additional features that improve their acceptability and usefulness over a wider range of applications. The following features, discussed in greater depth below, are available on most occupancy sensors:

- Manual ON mode

- Automatic mode
- Auxiliary contacts
- Annunciators and warning signals
- Fail ON function
- Masking labels
- Combined dimming/occupancy sensing in wall switches

Manual ON Mode

While most occupancy sensors are capable of switching lights on as well as off, it's often desirable to deactivate the automatic ON feature so that the lights switch on only if the occupant chooses it. This mode is also called manual ON/auto OFF. Energy is saved if the occupant decides not to use overhead electric lights because of adequate daylight or task lighting. As it is more energy efficient than fully automatic mode, manual ON may be preferred for building spaces such as private offices that are occupied by one or two people, or for spaces such as classrooms where there is considerable daylight. Most modern sensors allow the occupant to turn lights off manually whether they remain in the space or not.

With manual ON operation, it's important that the sensor be able to guard against false OFFs. If a false OFF occurs, the occupant may be forced to get up and walk to the switch to restore lighting, and may disable the sensor if false OFFs occur frequently. Some manufacturers use a grace timer that allows an occupant 5 to 10 seconds to make enough motion to reactivate the lights once they have been extinguished.

Automatic Mode

Automatic mode turns lights on upon occupancy and off upon vacancy. This may be preferred for spaces that are shared or used by several people at different times of the day. For example, the ceiling lighting system for an open office area with cubicles should be operated on automatic mode, since it's desirable for the overhead lights to go on when anyone enters the general area. It is also recommended for spaces where no daylight is available.

Some automatic-mode occupancy sensors have a simple photocell that can detect available daylight. In this application, the occupancy sensor will not automatically switch on the lights upon occupancy if the detected daylight is above some threshold value. The threshold value can usually be fine-tuned for a particular application. This feature, however, does not earn power reduction credits in many building codes when it is incorporated into a wallbox sensor because it can be easily overridden by the occupant if they become dissatisfied with their light level. A more precise and occupant-friendly method can be found in 8.4 – Daylighting Controls.

Auxiliary Contacts

Some switchpacks and/or sensors contain an extra switch or set of contacts so that more than one load can be controlled by a single occupancy sensor. An extra set of contacts can be used to switch an HVAC load, such as an exhaust fan, or provide a contact closure to a building management system. A few manufacturers offer a second set of contacts in their wallbox-mounted occupancy sensors. This is useful for applying occupancy sensing to spaces already equipped with dual switching (see section 8.3.5 – Application Guidelines for more information).

Annunciators and Warning Signals

Many occupancy sensors can indicate detection status using an LED built into the sensor or using an audible sound. An indicator light, usually an LED, will indicate when the occupancy sensor is actually detecting motion. Status indicators on occupancy sensors are required under California's Title 24. Occupancy sensors equipped with an audible alarm will sound a quiet alarm shortly before extinguishing the lights. This reminds an occupant to move or wave an arm to prevent the lights from being switched off. This is useful for situations when the occupant may remain unusually still for a period of time, or for applications where the sensor's sensitivity has been calibrated to respond only to stronger movements. This feature is particularly important for sensors that are operated in the manual ON/automatic OFF mode if no grace period is included.

Fail ON Function

Sensors with this feature keep the lights on if the sensor fails. (Emergency and safety illumination should not be controlled by sensors due to the remote chance that a sensor might fail and turn off the emergency lights.) Since no system is foolproof, it's still a good idea to not use occupancy sensors on all luminaires, so as to have some illumination if a system failure extinguishes the controlled lights.

Masking Labels

PIR occupancy sensors often have masking labels that allow the installer to fine-tune the coverage range of the sensors in applications where extraneous motion causes a sensor to false trigger ON. For example, if an open door leads to a hallway within the sensor's line of sight, a masking label could be used to deaden the sensor's response in the direction of the doorway. A preferable method is to accomplish this electronically by reducing the sensitivity, automatically, when a room is vacated so that motion in the hallway will not be detected. When a person steps across the threshold, the lights are turned on and the sensitivity is automatically increased to its original setting.

Combination Dimming and Occupancy Sensing in Wall Switches

Products that combine occupancy sensing and dimming control in a wallbox unit are now available. These switches, which fit in a standard wallbox, allow the connected lighting circuit to be dimmed as well as be automatically controlled using an occupancy detector mounted in the switch. This solution is particularly appropriate for retrofitting. However, the dimming functionality requires that a specific type of dimming ballast be used.

8.3.4 Commissioning Adjustments

Most occupancy sensors require commissioning upon installation to adapt the sensor to the specific space. Commissioning reduces the number of false ONs and false OFFs. A false OFF occurs when an occupancy sensor switches off lights while the space is still occupied. A false ON occurs when the sensor switches on lighting when the space is not occupied. Virtually all sensors allow adjustment of sensitivity and the time delay period. The adjustment device should be located so that it is accessible to the contractor performing the commissioning but not so accessible that unauthorized personnel can interfere with it.

Sensitivity to Motion

With the sensitivity adjustment, the sensor can be fine-tuned to accommodate the activities being performed in the space, the presence of air currents or drafts, and the distance of the sensor from the person being detected. If the sensitivity is correctly set for the application, false OFFs and ONs will be minimized. Some of the newer sensors perform this adjustment automatically.

Sensors commonly encounter changing ambient conditions that can affect their ability to detect moving heat. Some sensors incorporate an adjustable sensitivity feature that helps the sensor perform more consistently year round. The range of this sensitivity adjustment is typically 80–120%. If there is a false detection, the sensor will automatically increase the detection sensitivity.

Timeout Adjustment

The time delay adjustment allows changing the time period between when the sensor last detects occupancy and when it turns the lights out (often called the timeout period). Many systems come factory preset with a 10-minute timeout, which is reasonable for many applications. If the lights cycle often because an occupant frequently moves in and out of the space, the time delay can be set longer to mitigate any potential shortening of lamp life.

Some manufacturers produce sensors that can adapt the timeout delay according to the usage patterns in the room. If a room is used infrequently, the sensor will set a short time delay. If the room is used more often, the time delay will lengthen.

Sensors Requiring Minimal Commissioning

Since about 1995, several manufacturers have been producing occupancy sensors that are designed to require little or even no commissioning after installation. These new sensors commission themselves using one of two alternative methods:

1. The older of the two methods works by recording the duration of time between movements by the occupant. The time delay may be set manually or left at the minimum delay of 15–30 seconds. If a false OFF occurs and is immediately followed by an ON activation, the logic in the sensor assumes that the time delay setting is inadequate. The time delay is then set at the maximum setting of 30–60 minutes. The time delay is gradually shortened over days or weeks until an optimum setting is determined. This method may result in an average time delay considerably longer than necessary.
2. A newer method utilizes “real time” adjustments. If the time delay is manually set at 15–30 seconds by the contractor for testing purposes, after a short period of time (usually one hour) the time delay is automatically set for 10 minutes. Thereafter, any time a false OFF occurs, the time delay is immediately advanced by one or two minutes. This method avoids unnecessary, lengthy time delays and adapts quickly to the behavior of most occupants.

In addition, these self-adjusting sensors will maintain constant coverage by varying sensitivity as changes in the environment are detected. Note that these sensors usually do not "know" what the time is. Rather, they simply keep track of cyclical events (such as lights on and light off durations) and adjust the parameters within these periodic patterns.

8.3.5 Application Guidelines

The biggest application pitfalls associated with occupancy sensors are caused: (1) by using inappropriate sensor sensitivity patterns for the application; (2) by mounting the sensor in an improper location; or (3) by incorrect commissioning or no commissioning. Since occupants may disable lighting controls if they find them to be obtrusive, thus negating any energy savings, it’s important to address these potential pitfalls with good installation and commissioning practices. Commissioning is covered in sections 8.1.6 and 8.3.4. This section discusses techniques for specifying the correct sensitivity patterns and mounting locations.

Sensor Locations and Limitations

Once the decision has been made to use occupancy sensors, the most important design consideration is the detector's location. With wallbox sensors, because they are limited to the location of the wall switch, it's important that there be no obstructions to limit their effectiveness.

Ceiling-mounted sensors should always be mounted and positioned so that they activate the lighting system as soon as a person enters the space. Ceiling-mounted sensors may be mounted high on the wall as well as on the ceiling. Mounting the system high has two advantages: there are fewer possible obstructions, and the system will be easier to install because it's near to the electrical distribution system. Don't mount sensors in locations that may temporarily obstruct the detection pattern, such as behind door swings. And don't mount them so that they monitor areas outside of the controlled space. This could be a problem, for example, if a sensor were facing a doorway leading to a corridor.

To reduce the possibility of false detection, mount PIR sensors no closer than 4–6 ft from HVAC air diffusers or other heat sources. Do not place ultrasonic sensors close to ventilation air diffusers or open windows, where air movement may cause false triggering.

Similarly, the rated range of ceiling-mounted sensors should be derated when they are located in partitioned spaces, where barriers block the line of sight of the devices. For example, in spaces equipped with partitions of 48 in. or higher, the range of ceiling-mounted sensors will be reduced by more than 50%.

Table 8-7 – Recommended Applications for Occupancy Sensors

Sensor Type	Applications	Notes
Ceiling Mount	Open partitioned areas, small open offices, file rooms, copy rooms, conference rooms, restrooms, garages	Provides for 360° coverage; derate range by 50% if partitions >48 in. are in place.
Corner Mount/Wide View	Large office spaces, conference rooms	Mount high on wall.
Wall Switch	Private offices, copy rooms, residences, closets	Especially suitable for retrofits. Not recommended for areas with obstructions.
Narrow View	Hallways, corridors, aisles	Work best if mounted on centers with range control.
High Mount Narrow View	Warehouse aisles	Must be set back from aisle so that they do not detect motion in cross aisles.

Test installed occupancy sensors in all applications for sensitivity both initially and at intervals to ensure that specified performance is met and has not deteriorated or been compromised by environmental factors.

Energy Savings Potential for Occupancy Sensors

In 1997, researchers (Maniccia et al. 2000) examined the energy savings potential for occupancy sensors in buildings distributed across 24 states representing a typical cross section of commercial building stock. Occupancy and lighting ON hours were measured in 158 rooms: 42 restrooms, 37 private offices, 35 classrooms, 33 conference rooms and 11 break rooms. Each room was measured for about two weeks (between February and September 1997). The occupancy sensors installed did not actually switch the lights ON and OFF according to occupancy. Rather they simply logged when the rooms were occupied and whether or not the lights were (manually) switched ON.

The data collected is the first detailed reported study of when different space types are occupied throughout the day and when those spaces are lighted.

The table below gives the savings potential for occupancy sensors in the five space types during normal hours and after hours.

Space Type	Savings Potential All Hours	Savings Potential Normal Hours	Savings Potential After Hours
Restroom	60%	18%	42%
Conference Room	50%	27%	23%
Private Office	38%	25%	13%
Break Room	29%	14%	15%
Classroom	58%	23%	35%

The figures on the next page show the percentage of time that the different spaces were lighted during occupied and unoccupied periods for the weekdays.

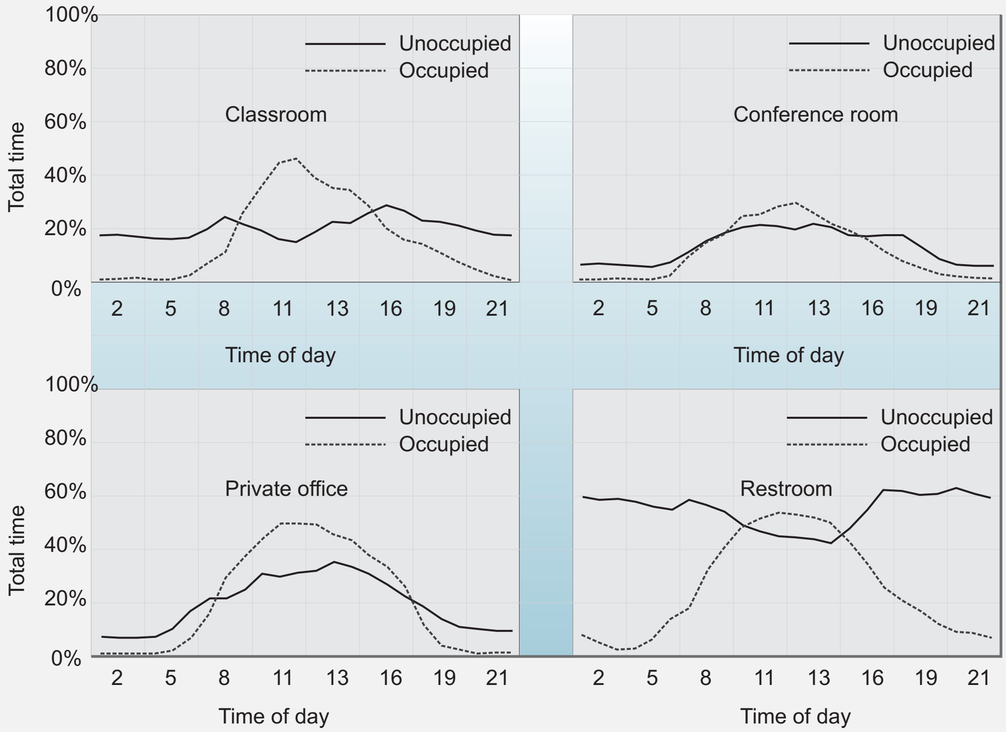


Figure 8-12 – Average Hourly Lighting Condition Profile

Average weekday lighting profile for occupied and unoccupied periods

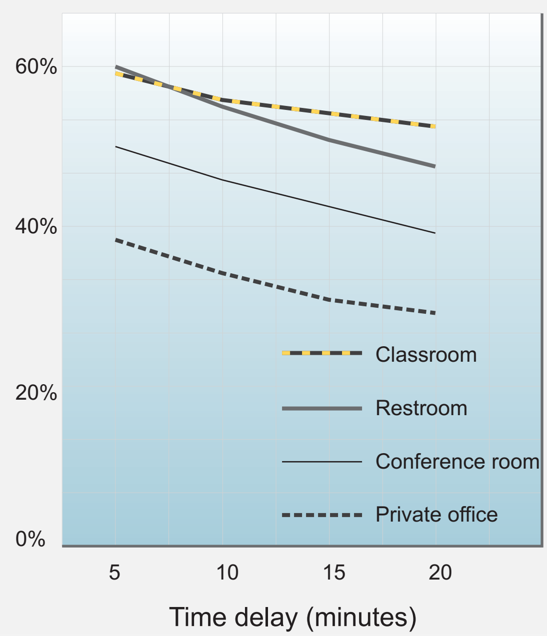


Figure 8-13 – Effect of Occupancy Sensor Time Out Delay on Energy Savings

Energy savings are reduced as the time delay is increased for occupancy sensor controls.

Appropriate Space Types

Areas that are unoccupied for long periods of time (as a rule of thumb, two or more hours per workday), and/or spaces where lights are likely to be left on inadvertently, offer the best application opportunities for occupancy sensors.

In commercial applications, single offices, conference rooms, break rooms and restrooms tend to have the most unoccupied periods. For retrofitting or major renovation, the greatest energy savings will be realized by installing wallbox occupancy sensors or ceiling sensors with manual ON capability (see section 8.3.3).

Offices occupied by more than one person or open office spaces will generally be occupied for longer periods of time than single offices. However, occupancy patterns in these areas are usually either constant or predictable, so a time-scheduling system might be a more effective control strategy. Nevertheless, occupancy sensors would also help to save lighting energy outside of normal work hours. Other generally occupied spaces that could benefit from occupancy sensors include school classrooms and corridors.

Many areas of offices, manufacturing facilities, schools, and other commercial buildings have no permanent occupants. These include copy rooms, filing areas, school classrooms, storage areas, conference rooms, warehouses and restrooms. Full lighting is required when in use, but people often don't turn off the lights when they leave the space. These types of spaces are excellent candidates for occupancy sensors.

Fail-safe or Backup Lighting

For safety's sake, it is important that a failure in the occupancy sensor's control unit sensor will not cause the lights to switch off. In addition, since complete fail-safe operation cannot be guaranteed, it's recommended either to leave some of the lighting uncontrolled by occupancy sensors or to install an emergency lighting system, so that people can safely leave the area in an emergency. Use backup "stumble" lighting in some form for any completely enclosed area, such as filing rooms, copy rooms, corridors and restrooms. Any luminaires that are connected to an emergency lighting system that is required by code should not be connected to an occupancy sensor.

Occupancy Sensors with Bilevel Switching

In retrofit applications, it is sometimes useful to add occupancy sensors to spaces where the lighting is controlled using bilevel manual wall switches (see also section 8.2). Several companies offer a wall replacement switch that combines the advantages of bilevel switching with occupancy sensing. With these switches, which can replace the two manual switches in a standard wallbox, two separate loads can be individually switched by the occupant manually or automatically via the occupancy sensor incorporated into the wall switch. See Figure 8-14.

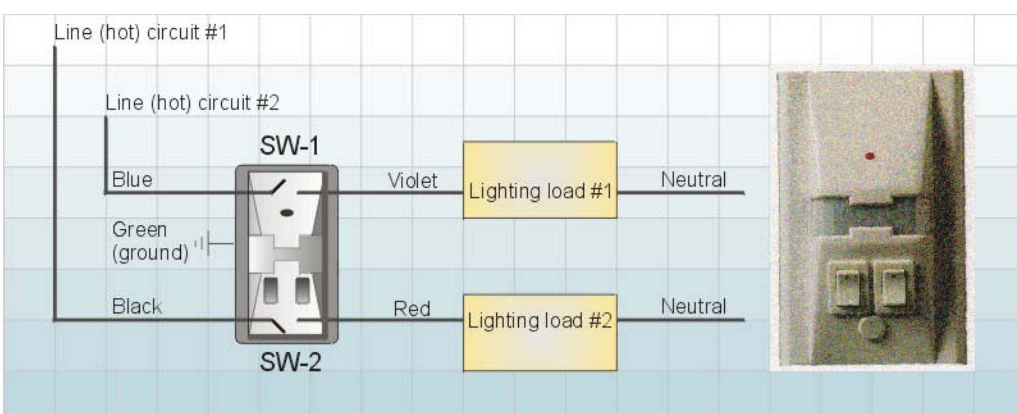


Figure 8-14 – Occupancy Sensors with Bilevel Switching

Wiring diagram for providing bilevel switching (left). Wallbox-mounted occupancy sensor with dual switching capability (right). Courtesy Unenco.

8.3.6 Documented Examples of Energy Savings from Occupancy Sensors

Although occupancy sensors have come to be considered a mainstream technology over the last decade, only recently have the energy savings from these devices been well documented in field studies. The results of three of these studies are summarized here.

National Center for Atmospheric Research (NCAR)

In a study of the NCAR building (Maniccia et al. 1999), the effect of occupancy sensors on lighting operating hours for 51 private offices was measured over several months using an in-place building management system. Using a 10-hour lighting schedule as the baseline, researchers calculated an average energy savings of 43% from the use of occupancy sensors alone. These savings occurred both during the day and at night. At night, occupancy sensors there reduced lighting hours that would have been wastefully provided by a simple scheduling system. During the day, the occupancy sensors reduced lighting hours by switching off lights in rooms when occupants vacated their offices temporarily. Additional energy savings occurred when occupants did not use their electric lights because they judged available daylight to be adequate and when the occupants used manual dimmers to reduce their light levels.

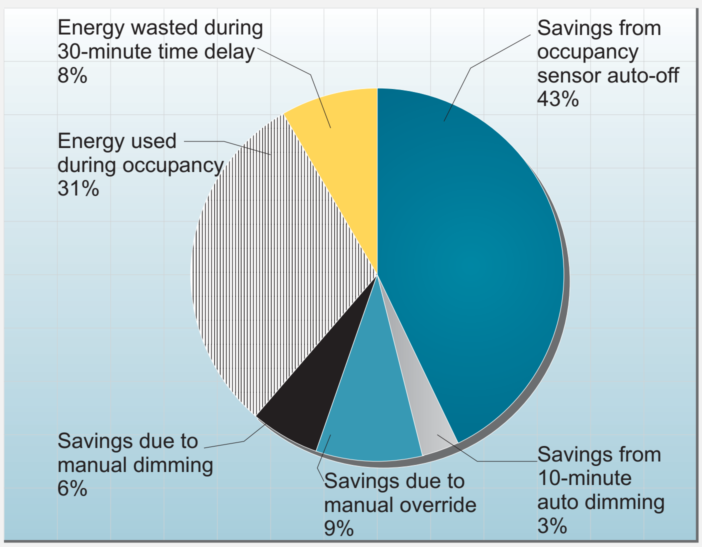


Figure 8-15 – Lighting Controls Energy Savings, National Center for Atmospheric Research

San Francisco Federal Building

In this lighting controls study (Jennings et al. 2000), the energy savings from occupancy sensors installed in 35 private offices was measured over seven months. The daytime energy savings attributable to the occupancy sensors were determined by comparing the actual daily lighting operating hours with occupancy sensors, to the estimated lighting hours (baseline) that would have occurred in the absence of the occupancy sensors. The baseline hours represents the interval between when the individual first switched on her lights in the morning, and when the lights were finally switched off in the day (whether by occupancy or manual wall switch).

The average energy savings attributable to occupancy sensors during the day was found to be 20–23%. The distribution of energy savings from occupancy sensors for 21 offices is given in the figure below. The fact that the occupancy sensors at this relatively tightly run building reduced wasted lighting significantly during the day indicates that the widespread use of occupancy sensors could be an effective means to improve the overall reliability of the electricity grid.

Researchers did not attempt to determine whether additional energy savings might accrue from the operation of occupancy sensors at night. Frequent "switch off the lights" campaigns in this building had sensitized building occupants to the need to conserve energy so that wasted after-hours lighting were largely eliminated in some private offices by occupants conscientiously switching off their lights. In other words, the savings achieved differs from what would be reflected in an office building without such "switch off the lights" campaigns and energy-sensitized occupants.

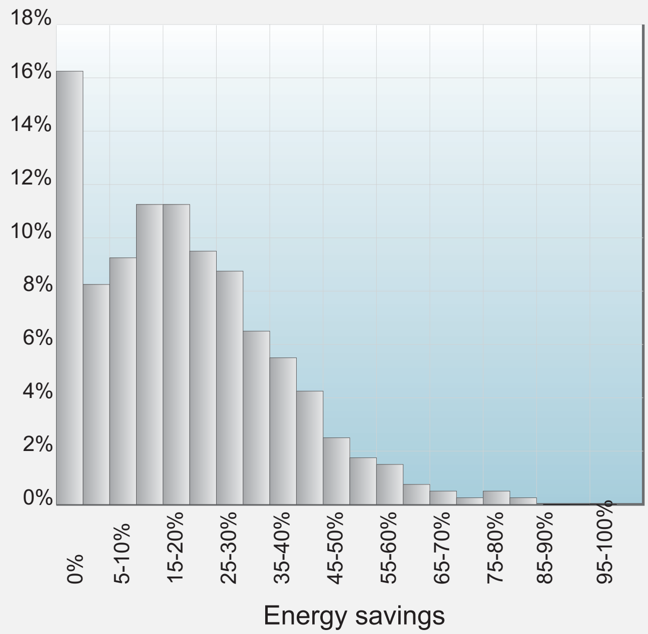


Figure 8-16 – Lighting Controls Energy Savings, San Francisco Federal Building

The distribution of energy savings obtained using occupancy sensors in a sample of 21 private offices over seven months at the San Francisco Federal Building.

Wisconsin Admin Building

At this University-operated office building, occupancy sensors saved about 15–20% in private offices (Pigg et al. 1994).

However, researchers also determined that the proclivity to switch the lights off manually was a function of the length of the subsequent absence: for very short absences (less than 30 minutes), the presence of an occupancy sensor made no difference in how often people turned the lights out when they exited. But for longer absences, people without occupancy sensors were more likely to switch the lights off manually. This suggests that under some circumstances, people in offices with occupancy sensors may tend to become less conscientious about switching off their lights when leaving than people in offices with manual switches only. The occupants' behavior suggests that the technology needs careful application in order to optimize energy savings and system functionality.

8.4 Daylighting Controls

Daylighting controls are devices that regulate the level of illumination provided by electric lights in response to the presence of daylight. They usually consist of a sensing device (photocell or photosensor) that monitors either the total light level in the space or the available daylight level at the daylight aperture, and a control module that then switches or dims the electric lighting to maintain the needed illumination with minimal energy use.

This section focuses specifically on daylighting controls. For details about daylight as a light source and daylight availability, see section 6.3. For details about advanced daylight systems, refer to section 7.4. In addition, many of the models shown in chapter 5 demonstrate advanced daylighting design.

8.4.1 Introduction

The use of daylight as a source of illumination in commercial buildings offers tremendous potential for creating beautifully lit interior spaces that yield substantial energy savings. Nonetheless, daylighting per se saves no energy unless the electric lighting system is appropriately controlled. Since daylight may be present in large areas of commercial buildings for many hours of the day, automatic photoelectrically controlled lighting systems can easily save 10–50% of the annual lighting energy, reducing both building operating costs and consumption of natural resources. Equally important, since daylight availability usually coincides with the utility's peak demand profile, daylight controls can also reduce peak demand charges (for more about peak demand charges, see section 3.1.4).

Figure 8-17 shows lighting power as a function of time of day for clear and partly cloudy daylighting conditions for an office building in San Francisco, while Figure 8-18 shows average daily lighting energy for a six-month period in the same building.

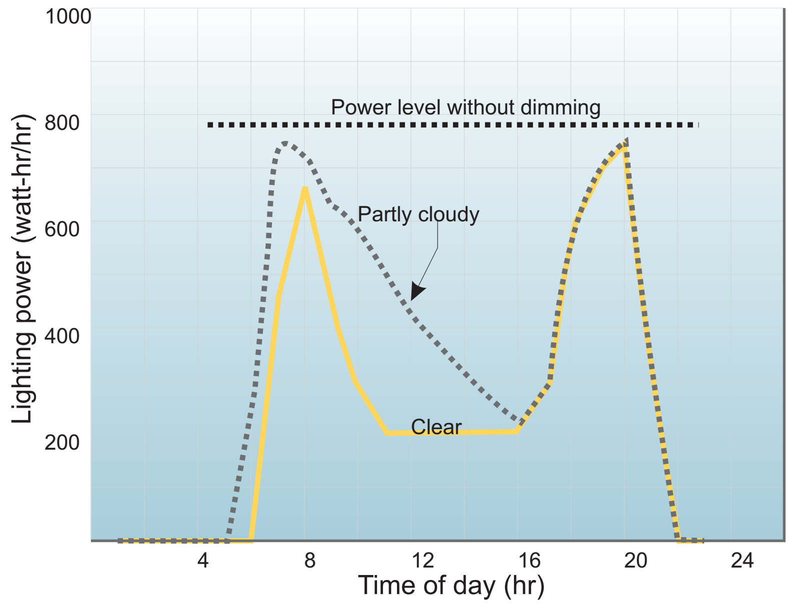


Figure 8-17 – Lighting Power as Function of Time of Day
For a row of dimming luminaires nearest south window, San Francisco Federal Building, for clear and partly cloudy daylighting conditions in September 1997. (See section 8.3.6).

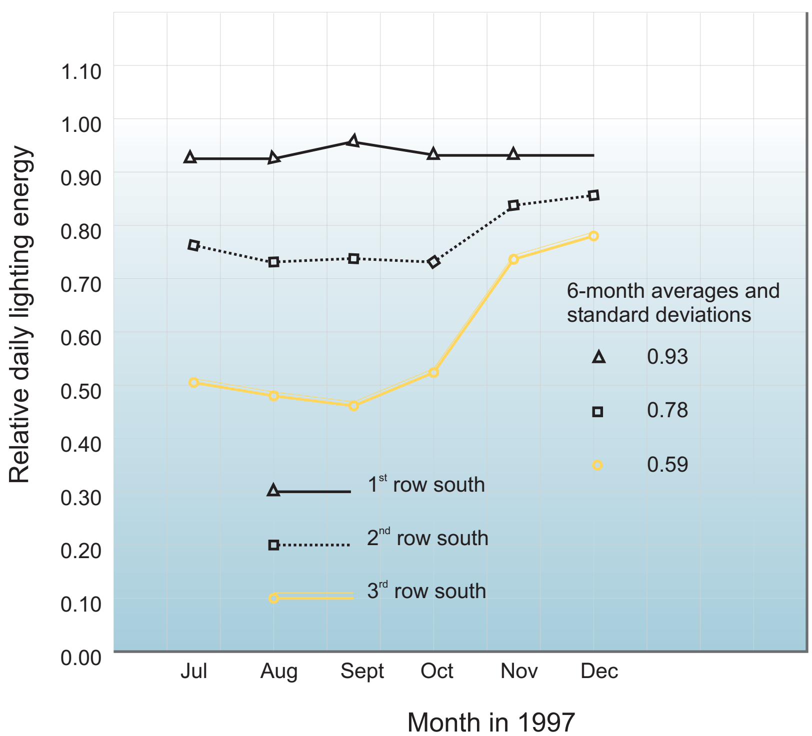


Figure 8-18 – Daily Lighting Energy, San Francisco Federal Building
Shows average daily lighting energy at the San Francisco Federal Building for six months in 1997 for three rows of dimming luminaires on the south side. (See section 8.3.6).

Beyond energy savings, the goal of any lighting control should be to increase lighting quality and give the occupants expanded flexibility to customize the lighting environment for specific visual tasks and moods. Implemented well, daylighting controls help to balance luminance ratios across the space and reduce conditions of overlighting. Furthermore, once a dimming system has been implemented for daylighting control, it can be used to “fine-tune” specific areas for higher or lower light levels or to give the occupant manual dimming control of the system. The cost of this expanded level of occupant control is minimal once the basic photocontrol equipment costs have been justified by the daylighting energy savings.

Occupant control over the environment may correlate with greater satisfaction, higher productivity and reduced absenteeism—financial benefits that can eclipse the magnitude of energy savings. However, a poorly performing automated system can actually reduce occupant satisfaction and productivity. Thus, it's essential that the building owner be committed to ensuring that the system is properly designed, commissioned and maintained. The simplest systems are often the most cost effective and reliable. Photocontrolled multilevel switching has been successfully employed in hundreds of retail, warehouse and industrial spaces. Photocontrolled dimming systems require a greater investment, and are most frequently employed in offices and other high-end occupancies.

8.4.2 Control Techniques

In designing a daylighting control system, the specifier must decide whether to use dimming or switching, and upon the level of automation.

As noted in section 8.1.3, on/off daylight switching is the most economical approach, but may create unacceptably abrupt light level changes in work areas. It is most successful in circulation areas like atria, entryways and walkways with transient occupation and non-critical tasks. More gradual light level changes can be accomplished with multilevel switching schemes where the change in illumination due to switching is at or below the perceptible level. Thus, the greater the number of levels employed, the greater the likelihood of user acceptance. A greater number of switching levels also produce increased energy savings, as the system becomes more responsive to modest changes in daylight illumination. The most common systems employ four levels of illumination: fully off, 1/3 light output, 2/3 light output, and full light output. These levels are easily achieved with three-lamp fluorescent troffers. They can also be achieved with new multilamp CFL luminaires designed for low and mid-bay applications. (See chapter 7 for information about specific luminaires.)

Multilevel switching of HID luminaires usually involves switching individual luminaires, which can cause irregular lighting patterns within a space and may be impractical due to long restrike times. In this case a hybrid, hi-lo system, as discussed in section 8.1.3, may be preferable.

Dimming systems have higher costs, but will be more acceptable where occupants are stationary and concentrated on critical tasks. For fluorescent luminaires, expensive “architectural” dimming ballasts that can dim down to less than 1% are not required for energy conservation purposes; dimming to 5–20% is sufficient.

Savings

If daylight levels in the space are close to the desired illumination levels, daylight dimming controls will save more energy than switching systems. However, if daylight levels are substantially higher than target levels, a switching system will save more energy because it draws no residual power when it has switched the lights to an “off” position.

Multilevel photocontrolled switching systems are most cost effective in climates that have relatively uniform daylight conditions throughout the day. For example, in Southern California, most days tend to be either clear and sunny, or fully overcast, throughout the entire day. Thus, there is typically only one time each day that the photocontrols turn lights off or on in response to changing daylight illumination levels. Even HID switching systems have been very successfully employed in Southern California because the need for re-starting lamps is so infrequent. The new skylit production facility for REMO, Inc., one of the world's largest manufacturers of drums, uses photoswitching of 250-watt metal halide lamps in a checkerboard pattern across most of the production floor. Lights in some critical areas and half of the lights along the perimeter are always left on during working hours. The success of this installation is due to the consistent Southern California sky conditions, which minimize switching. Lights typically turn off in the morning and remain off for the rest of the workday (Southern California Edison 1999).

Dimming photocontrolled systems, on the other hand, tend to be most appropriate in climates that have highly variable cloud conditions throughout the day, and fewer days of peak daylight illumination conditions. Frequent changes from sunny to overcast require more frequent responses from the control system. In these climates, more energy is generally saved, and occupants are generally happier, with the more precise changes in light levels that can be achieved with a dimming system. The trade-off is often the inability to completely turn the lights fully off, which can substantially reduce the energy savings potential of the system.

Combined systems that dim the lights to a low level and then switch them off as daylight increases provide both gradual light level changes and optimum energy savings.

8.4.3 Integrated Design

Understanding Daylight Distribution

The first step in designing a daylighting control system is to understand the daylight distribution and the lighting needs for the space. It may be helpful to envision the lighting needs in terms of a layered lighting approach with task, ambient and accent functions. Within this framework, daylight usually provides ambient lighting for the space and integrates with the ambient electric lighting system. Thus, the control approach is also layered: the daylighting controls operate on the ambient electric light system; accent lighting is usually placed on a time schedule and task lighting may be manually controlled or occupancy sensed with one of the newer personal lighting controls.

Sometimes, daylight distribution appears uniform across the space. But more often, daylight levels vary across the space depending on distance from the daylight apertures (see Figure 8-19). The daylight intensity and distribution also change through time, depending on hour of day, season, sky condition (clear versus cloudy) and condition of blinds and shading devices.

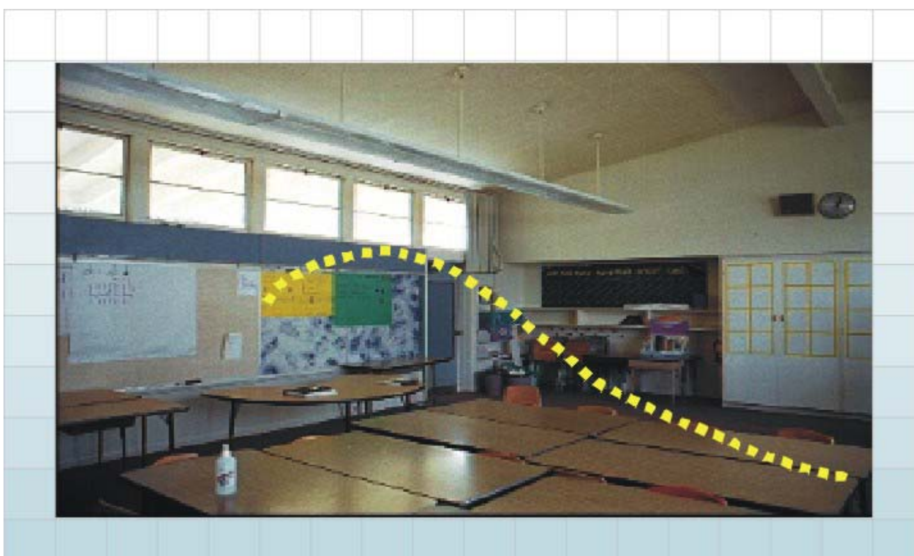


Figure 8-19 – Daylight Distribution in a Classroom
High clerestory windows provide good access to daylight across two-thirds of the classroom. Horizontal daylight illumination levels (dashed line) start out high near the window wall and fall off away from the wall. Pendant indirect luminaires parallel to window wall supplement daylight as needed.
Photo courtesy Lisa Heschong.

Ambient lighting needs may also vary across the space. Workstations, for example, may require 50 fc illumination while adjacent walkways may need only 20 fc. In the ideal situation, daylight gradients match the required changes in ambient illumination. But this ideal is rarely met; so ambient electric lighting should be designed and controlled to augment daylight in a graduated fashion as dictated by both the daylight distribution and the task requirements.

To do this, it's helpful to visualize the daylight gradients or isolux contours (lines of equivalent daylight levels) in the space. Figure 8-20 shows daylight contours for several generic daylighting strategies. Note that since daylight is additive, contours from adjacent apertures combine to create the overall contour pattern. Physical scale models, computer programs, graphical methods and full-scale mock-ups may be used to predict and plot daylight contours for specific configurations of windows and skylights. Some of these estimation techniques are described in section 4.4.2. These contours should be studied for the range of sun angles and weather conditions that the building will encounter.

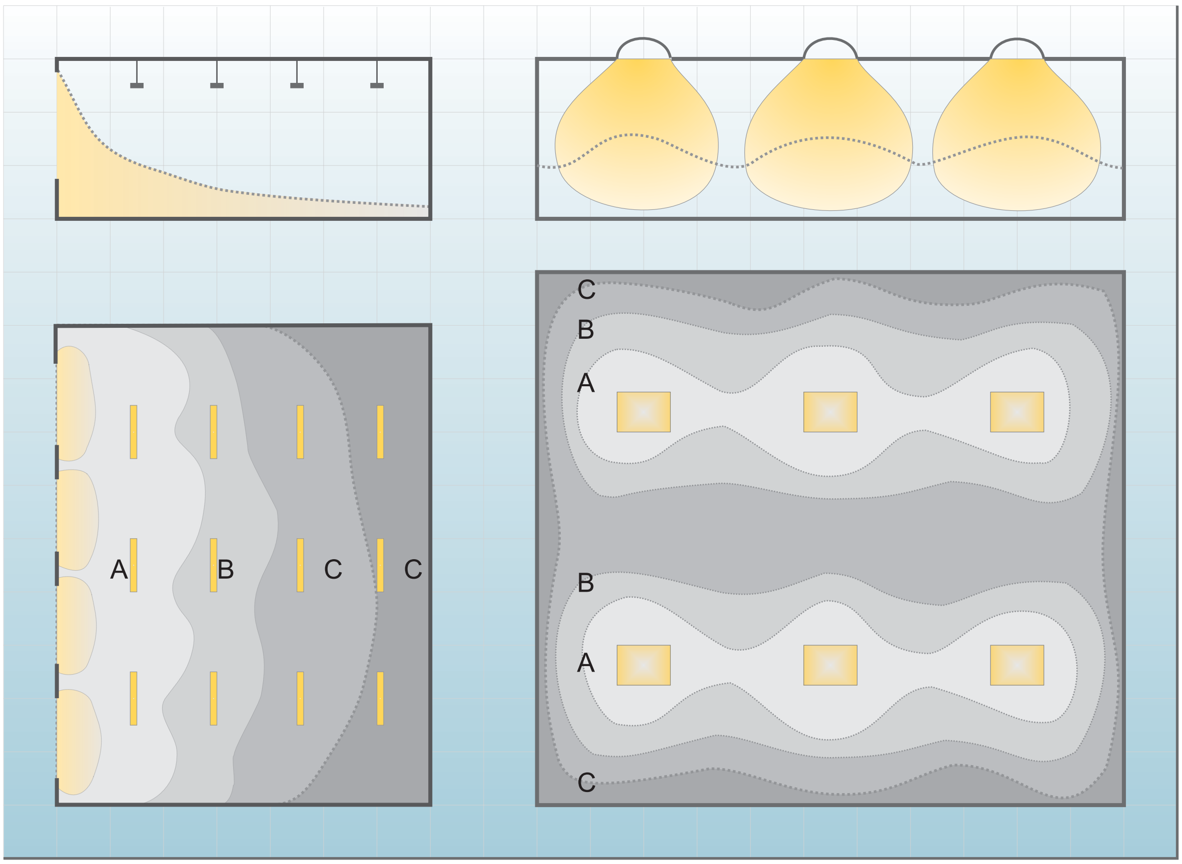


Figure 8-20 – Plan Views of Daylight Isolux Contours

Align control circuits parallel to daylight contours when daylight levels vary across the space. In these plans and sections of a sidelit office and skylit factory, "A" experiences the most daylight and is turned off or dimmed first; "B" is controlled second; "C" receives the least daylight and is left at full power to maintain wall brightness. The office pendant direct-indirect luminaires are dimmed in response to daylight; factory MH luminaires are bilevel switched. In the factory, the end luminaires on the B row are controlled with C circuit to maintain wall brightness.

Integration of Electric Lighting

The electric lighting system should be designed from the start with daylighting in mind. Lay out the lighting system in a pattern that mimics the daylight availability and is circuited parallel to the daylight contours. Although the newer addressable ballasts and low voltage control systems can create control zones independent of the circuiting, aligning the circuits with the daylight increases the options for control, reduces the expense of implementing a control system and creates a "visual logic" to the control zones. Figure 8-20 shows electric lighting aligned and circuited parallel to the daylight contours.

Control Zones

During the design phase, electric lights that are to be controlled together should be organized into control zones. All the lights in a control zone are dimmed (or switched) together and are regulated by one controller (and one photosensor). Zones should be determined by identifying areas with similar:

- Task illumination needs
- Lighting schedules
- Daylighting conditions
- Electric lighting systems
- Furniture or furnishings
- Likely future spatial arrangements

Ideally, each control zone should encompass an area with uniform daylight levels, task lighting needs and consistent management of shading devices (blinds, etc.). If these don't coincide, then smaller zones will need to be created and the cost of the control system will increase. For example, if adjacent windows are fitted with individually controllable operable blinds, it may be necessary to control the lights in front of each window separately. With the electric lighting zones formed this way, an occupant adjusting their blinds will only cause the electric lighting to change in his or her own area, and not in adjacent zones.

Mismatches between control zones and daylight availability can be costly. When Timberland, an outdoor clothing manufacturer, moved into a new 4,000,000-ft² skylit distribution center in California, the control circuitry was designed before the racking layout was finalized. As a result, some narrow rack aisles were under the control of a photosensor responding to more open conditions, leaving some of the aisles very dark. After they moved in, Timberland found it necessary to rewire the control circuits to coincide with the high and low racked areas (Southern California Edison 1999).

From an electrical standpoint, all the luminaires in a control zone should be on one lighting circuit or subcircuit (switchleg). Although some dimming photocell controls can mix dimming and non-dimming ballasts on the same circuit or can control dimming ballasts on different circuits, it is still best to identify a control zone with a specific circuit or subcircuit. This simplifies installation and leaves flexibility for future changes.

The size of control zones is limited by the electric current capacity of the lighting circuit. Typical control zones for a sidelit open office space and a skylit manufacturing facility are shown in Figure 8-20. The size of the control zone is an important consideration. Ideally, each parallel row of luminaires should be circuited separately, so that each row can be controlled in direct response to the availability of daylight in that particular area. The smaller the control zone, the more localized and responsive it will be, but also the more expensive. A large control zone will have a lower installed cost per watt of controlled lighting and thus a quicker payback period, at the sacrifice of control accuracy and future flexibility. The zone definitions must achieve a balance between these concerns.

Code Requirements

To reap the savings inherent in daylit buildings, many energy codes require separate controls for electric lights in daylight zones. ASHRAE 90.1 originally defined daylight zones for vertical glazing and toplighting apertures and required that electric lights within these zones have either separate switching or automatic daylight control devices. However, the new ASHRAE/IESNA Standard 90.1–1999 (issued in February 2000) removed these provisions; it currently has no requirements for separate control of electric lights in daylight zones. California's building energy efficiency standard, Title 24, also does not require separate or automatic daylighting controls. But Title 24 does offer credits for a reduction in the calculated installed wattage of electric luminaires that are controlled by automatic daylighting controls within a daylit zone. This effectively decreases the contribution of daylight areas to the installed wattage of the building.

Design Considerations

When designing lighting systems for interior spaces, some designers mistakenly assume that maintaining a constant level of illumination over the course of the day is the best design criterion. This may even be stated explicitly as a commissioning goal and a monitoring and verification performance objective in new building projects. This design criterion has slipped into the design of daylit spaces as well, for which it may be less appropriate.

Research at Philips Design and Application Centre in Eindhoven, Netherlands, indicates that office workers prefer light levels to change over the course of the day (van den Beld et al. 1997). Measurements showed that the workers preferred higher light levels during the day than at night, perhaps attempting to balance the surface luminances between the dark interior walls and brighter window walls. This is especially important in spaces that have vertical windows on one elevation only. In this situation, the back of the room may appear gloomy because the daylight gradient falls sharply with distance from the window. Regardless of why, the Philips research supports the use of photoelectrically controlled dimming systems that allow the total light level to increase somewhat as the daylight level increases rather than maintaining constant illumination. A good rule of thumb for the control system might be to subtract one lumen of electric light for every two or three lumens of daylight added to the space. This criterion, or another similar to it, can be accommodated by specifying a proportional control system (described in section 8.4.4 below) and properly commissioning it after installation to accommodate the users' preferences.

In addition to being circuited parallel to daylight contours, an integrated electric lighting scheme should deliver electric light to the same surfaces as the daylight in order to minimize changes in room surface brightness as the daylight controls operate. For example, in buildings that use lightshelves, the daylight bouncing off the lightshelf and diffusing from the ceiling serves as a form of indirect lighting. This type of daylighting is well matched with an indirect or direct-indirect electric lighting system that also uses the ceiling to diffuse and distribute the light (indirect systems are described in section 7.5.8; direct-indirect systems in 7.5.9). However, if an indirect electric lighting scheme is coupled with a direct daylighting scheme (a skylighting system, for example) or vice versa, then dimming or switching the electric lights in response to daylight may darken ceiling areas or wall surfaces in the control zones relative to the rest of the space. These surface brightness effects should be anticipated and avoided wherever possible.

Figure 8-21 – Integration of Electric Lighting and Daylight in Sidelit Office
In this sidelit office, electric light is delivered to the ceiling by indirect luminaires on the interior edge of the lightshelf, a pendant running parallel to the window wall and cove uplighting on the interior wall. This integrates well with the daylight, which also reflects off the lightshelf onto the ceiling. The indirect electric approach shields lamps from view and minimizes the visual impact as lamps are switched in response to daylight. In this photo, all electric light is off except the fluorescent cove lighting at right which balances the bright daylight above the lightshelf. Photo courtesy Richard A. Cooke, III.

With a switching scheme, it is also best if lamps that are switched off are not visible to occupants, as in indirect lighting systems. If this isn't possible, the designer should create a logical and aesthetically pleasing switching pattern. Lamps visibly extinguished in a random pattern give the appearance of poor maintenance or ceiling “clutter.“

As noted in Figure 8-21, for sidelighting schemes that are daylit from one side only (unilateral), ensure that the space's back wall is adequately lit (for example, with non-dimming wall-washing luminaires; see section 7.5.3). If the back wall isn't adequately lit, the room will appear gloomy even if the design light level is rigorously maintained at the control point.

8.4.4 Daylighting Control Components

Automatic photocontrol systems consist of the following components:

- *Electric light sources.* Critical decisions for the electrical lighting system include the type of source (fluorescent, metal halide, high-pressure sodium, etc.) and its switching and dimming characteristics, the type of ballast driving the light source (on/off, dimming, hi-lo), the wiring to the fixtures (standard, split), the number of luminaires per circuit, and the physical layout of the luminaires. (For information about specific sources and luminaires, see chapters **6** and **7**, respectively.)

- *Photosensor.* The photosensor automatically measures the light level within or entering the controlled building space. The photosensor generates an electric signal based on a sampling of the light in the space. The particular geometry of the photocell and its housing determines the sensitivity of the cell to light from different directions. *Controller.* The control unit translates the photosensor signal into a command to the dimming or switching control unit. The design of its control algorithm, deadbands and delays determine its responsiveness to varying lighting conditions.

- *Dimming or switching units.* These control units vary the light output of the electric system by turning off one or more lamps or altering the amount of power flowing to the lamps. A dimming unit may be incorporated in the ballast itself or may be separate from it. The switches (or relays) may be line or low voltage.

Control components may be housed separately or integrated to form a single package. For example, some dimming electronic ballasts can be coupled with a photocell that directly controls the ballast without the need for additional control gear.

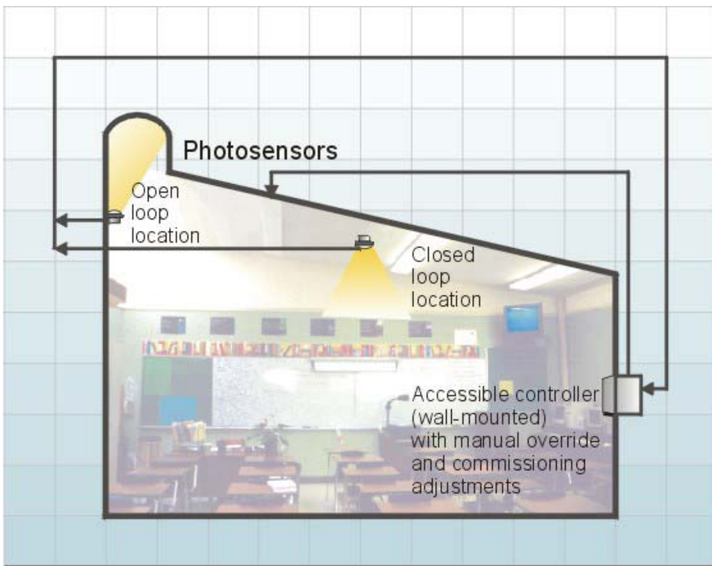


Figure 8-22 – Relationship of Photoelectric Dimming System Components, Typical Application
Diagram of photocontrol components for switching or dimming. For dimming, locate photosensor in either the closed-loop or open-loop location. Most switching applications would use the open-loop location.

Figure 8-22 illustrates how daylighting control components are interconnected in a building application with a common mounting configuration for the control photosensor. The ceiling-mounted photosensor links the ambient light levels in the space (both electric and daylight) to the controller, which then adjusts the electric light output according to its built-in algorithm.

Photosensors

Photosensor Types

Automatic daylighting control systems use a photosensor to measure illumination within or entering the space. There are two basic types of photosensors: photodiode and photoconductive. Photodiode sensors produce a voltage that is directly proportional to the detected light. Some products may be adjusted to more sensitive or less sensitive settings. Photoconductive sensors produce a voltage that is inversely proportional to the detected light in a roughly exponential relationship.

Although photoconductive sensors are less expensive than photodiodes, they are very non-linear in response and therefore much less accurate. However, photoconductive sensors can be specified to have a light level sensitivity range with some tolerance. The appropriate range to specify depends on the mounting location and field of view. Because of their limitations, photoconductive sensors are used primarily in controlling nighttime outdoor lighting and indoor switching applications that do not require precise light level control. Photodiode controls should be used in switching and dimming applications where more precise light level control is important.

Color Correction and Spatial Response

For accurate light control, the photosensor should also be color-corrected so that it closely matches the human eye's sensitivity to different colors. This is known as photopic (or color) correction. Since daylight and electric light have different spectral distributions, the better the photosensor mimics the human eye's spectral response, the less likely it is to misrepresent the balance of daylight and electric light. Recent research indicates that many commercially available photosensors have a broader response than the photopic curve (Bierman 2000). This means that these systems may tend to undersupply electric illumination, which may lead to occupant complaints about low light levels.

The area of light sensed by the photosensor is its "field of view" and is determined by the design of the lens, prism, or fiber optic system that gathers and conveys light to it. If the field of view is too narrow, the sensor will be overly sensitive to localized changes in illuminance, such as those caused by a bright white paper placed on a desk underneath it. If the field of view is too wide, the sensor may detect direct sunlight near (or outside) the window and dim the interior lights prematurely. A 60 degree cone of vision is common. Some sensors also come equipped with an adjustable "sun shield" or collar to block the sensor's view of direct sunlight. Others provide photosensors that are ceiling mounted but are aimed toward the window wall to measure the ambient light coming through the window. Carefully follow the manufacturer's installation instructions.

Recent and ongoing work is attempting to characterize the performance characteristics of photocells, dimming control algorithms and ballast performance for commercially available products. See, for example, National Lighting Product Information Program 1998; Mistrick 2000; and Bierman 2000.

Some examples of the spatial response of several commercially available photosensors are shown in Figure 8-23.

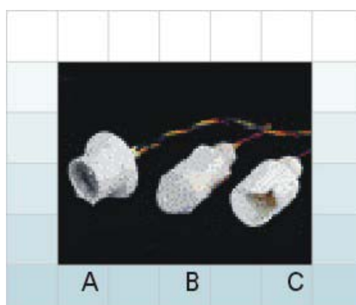


Figure 8-23 – Examples of Photosensors

Common types of commercially available photocells include: A) Fresnel lens, 60 degree cone of vision; B) Translucent dome, 180 degree cone of vision; C) Shielded sensor. Photo courtesy Multipoint.

Placing the Photosensor

Placement of the photosensor depends on the application. Some photosensors look directly at a task surface or an interior wall and sense the combination of daylight and electric light reflected off that area. Other photosensors are located on top of a building or view directly out of a skylight or window aperture, sensing only the available daylight. Both the illumination levels incident on the photocell and the response algorithm vary considerably depending on these mounting conditions. The following guidelines give some rules of thumb for placing photosensors. These are generic guidelines only, however, since there are many possible combinations of application and control type. Carefully follow the manufacturer's instructions.

- *Daylight availability:* Mount the sensor so it sees a good representation of the daylight available to the space.
- *Exterior photosensors:* Be aware of obstructions that may shade the sensor at different times of day. If the daylight apertures are not similarly shaded, the photosensor will give misrepresentative light signals to the lighting control system.
- *Skylighting applications:* Locating a photosensor under a skylight glazing is generally better than above it because the sensor is protected from the weather and it senses the available daylight through the filter of the glazing, including any dirt accumulation.
- *Sensors mounted in skylight wells looking up out of the well:* Use a standoff to position the photosensor at least 1 ft from the nearest face of the skylight well so that it is not shadowed by the skylight curb.
- *Ceiling-mounted photocells in sidelighting applications:* As a rule of thumb, place the photocell at a distance away from the window equivalent to approximately two-thirds the depth of the daylight control zone. In spaces where there is only one major task area, locate the ceiling-mounted photosensor above the task. If there are several tasks areas separated by some distance, locate the photocell above a task area that receives a representative amount of daylight. A better (but more expensive) solution is to use separate control zones for each area.
- *Sidelit buildings with lightshelves:* Mount the photosensor above the lightshelf pointing down so that it detects daylight reflected from the top of shelf. (See, for instance, Benton 1989.)
- *Indirect and direct-indirect lighting systems:* Most photosensors should not directly view the electric lights they control. For indirect and *direct-indirect* lighting systems, make sure the photosensors are not mounted above the lights with a direct view into them.
- *Sensitivity range.* Choose a photosensor sensitivity range that matches the light levels expected for its particular mounting location. Photosensors mounted on a rooftop may detect over 8000 footcandles on clear sunny days. This value will be attenuated by the glazing transmission and reduced angle of view for photosensors looking up through a skylight. For interior, ceiling-mounted photocells looking down at a task area, the photosensor will receive about one-fifth the illumination incident on the task

Photodimming Units and Controllers

In operation, automatic daylighting systems dim electric lights as the amount of light striking the photosensor increases. Exactly how much the lights dim for a given change in detected light is determined by commissioning the daylighting system. Because daylight frequently enters the space from a different direction than electric light and has a different spectral distribution, it is necessary to commission the system response to account for local conditions. Out of the box use is usually not possible.

It is usually necessary to commission daylighting systems under two different conditions: usually at dusk and during the middle of the day. Dusk conditions can sometimes be simulated by closing all blinds etc.

Figure 8-24 shows an idealized relationship between control voltage (electric light output) and photosensor illuminance for a proportional controller driven by photosensors operating in either open- or closed loop modes. Proportional controllers impose an approximately linear relationship between the electric light output and the photosensor signal. Properly-designed controllers allow the commissioner to adjust (1) the maximum electric light level, (2) the minimum allowable dimming control voltage and (3) the sensitivity or gain of the controller response (how much the electric lighting system will dim for a given change in photosensor illuminance). When adjusted to maximum sensitivity, a small change in detected photosensor illuminance causes a large change in control voltage.

Commissioning a daylighting system requires adjusting the sensitivity to accommodate the local daylighting conditions.

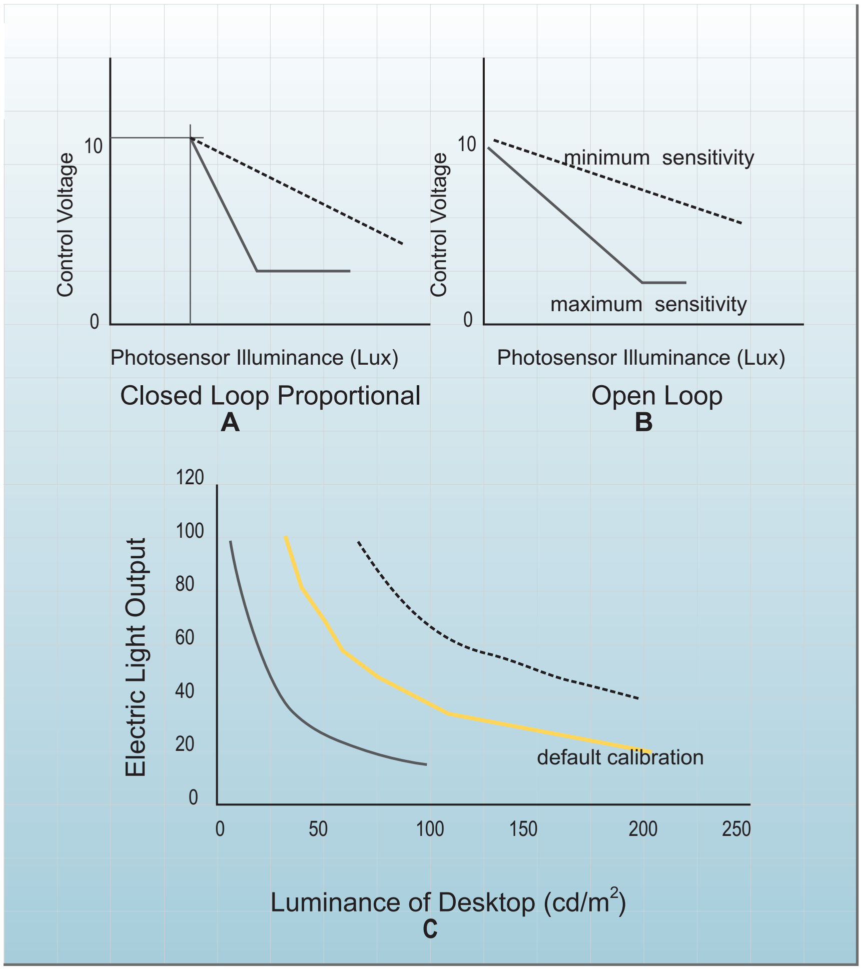


Figure 8-24 – Relationship of Dimming Control Voltage to Photosensor Illuminance
Shown for idealized proportional controllers driven by photosensors operating in: (A) open-loop, and (B) closed-loop modes. In closed-loop mode, the photosensor is able to detect the electric light and therefore the photosensor illuminance is calibrated with an offset. (C) shows the relationship between the luminance of the desktop below the photocell and the resultant electric light output plotted for three positions of the calibration sleeve. Data from Van Bogaert 1996.

New Luminaire-based Photocell Controls

In 1998, a new type of photocell control became available in the United States. (These controls have been available in Europe for some time.) They consist of a photocell in a housing that clips onto the lamp in open and louvered luminaires (see Figure 8-25). Each photocell is connected to the low-voltage leads on a controllable ballast and they may not be connected parallel, so every ballast to be controlled requires a corresponding photocell. Since they are relatively inexpensive (approximately $15 per unit), they provide fine dimming control over individual luminaires.

In operation, these luminaire-photocell controls allow implementation of daylighting and tuning simultaneously with the same piece of hardware. For example, upon installation, the installer could adjust the maximum light output delivery of individual luminaires to meet the expected use of the immediate space. In general, it is much more likely that the local occupants' lighting needs could be determined immediately after installation of the new lighting controls than it could be during the building design phase. Thus, during commissioning, these controls offer the energy service provider the opportunity to adjust the maximum electric light level immediately after the new lighting controls have been installed. As the top dimming range for each luminaire is adjustable with this type of control, the local lighting environment near each luminaire can be individually accommodated. For example, if luminaires are located over circulation areas where lower light output is acceptable and even desirable from an adaptation viewpoint, these luminaires can be selectively "tuned down," thus saving lighting energy.

Figure 8-25 – Luminaire-based Photocell Control

In addition to providing a convenient means to tune individual luminaire output, this photocell control also responds to changes in available ambient light. As the amount of available daylight increases, the control automatically reduces the electric light output.

As the size of the sensor response and control zone is reduced, response precision increases. This trend is likely to lead to greater user acceptance and more optimum energy savings. There are likely to many more developments in this area in the near future, as sensors are miniaturized and reduced in cost, and as control logic increases in complexity and sensitivity.

Photoswitching Units and Controllers

Hardware

Photoelectric control switches can be used to switch off one or more lamps in luminaires within a daylight zone when a preset “threshold” light level has been exceeded. They may also be wired to switch off an entire row of luminaires or alternate luminaires in a pattern across the space. A common technique for achieving stepped daylight switching from a multilamp fluorescent system is to use split (or tandem) wiring that shares ballasts between adjacent luminaires (see Figure 8-5). This allows switching of individual lamps while minimizing the number of ballasts used.

Switching units are usually low-voltage relays and may be located above a drop ceiling or in an electrical closet.

Switching Algorithms

A setpoint control algorithm is used with switching systems to determine at what daylight levels the electric lighting will switch on and off or step up and down. Photoswitching systems are calibrated in the field to adjust the setpoint or threshold light level at which switching occurs. Clearly, the threshold must be set sufficiently above the target illumination level so that the target is maintained after the switching is accomplished.

As a rule of thumb in high-ceiling applications, people don’t generally notice changes in illumination levels that are less than one-third of the current illumination level. Thus, if illumination levels are set at 100 fc, most people will probably not notice an increase to 130 fc or a decrease to 70 fc.

To minimize “cycling” (rapid on/off switching) of lights, the switching scheme should also incorporate a “deadband” (a zone of light levels in which no switching can occur). This deadband is created by an offset between the levels at which the lights are turned off and turned back on (see Figure 8-26). This deadband stops the lights from cycling between on and off if the ambient light level is near the threshold level.

The deadband must be larger if the photoswitch is positioned so that it senses the electric light that it is controlling. If the deadband is not sufficient and the light level change caused by the lights switching on and off is large enough, there can even be light levels at which the system will be unstable. This will cause the lights to cycle between on and off states until the ambient light level increases enough to bring the system out of the unstable region.

Some photoswitches also allow the user to adjust a time-delay constant that causes the sensor to wait a prescribed period of time between when the light level is detected and when the switching occurs. This lag time reduces the likelihood of cycling and rapid switching due to intermittent cloud conditions.

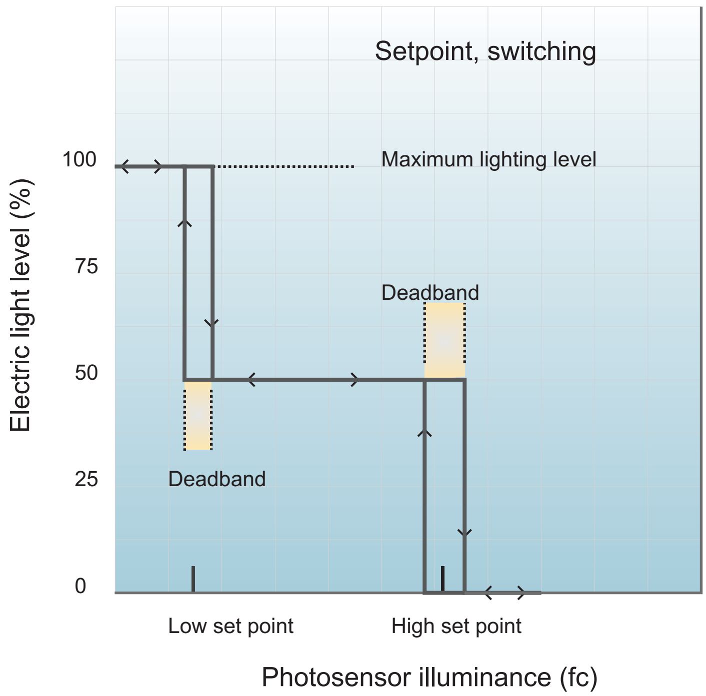


Figure 8-26 – Switching Photosensor Illuminance and Electric Light Level
Shows relationship between switching photosensor illuminance and resultant electric light level, and the effect of deadband on system response.

8.4.5 Evaluating Savings

Evaluation of the energy savings of daylighting controls may involve measurements with scale models, estimates with simple spreadsheet programs, hourly building energy simulations or full-scale mockups. Because daylight availability will change with time of day, weather and season, simulated spaces need to be studied with the variety of daylight conditions they will encounter. This information must then be compared with the target illumination levels and annualized to predict the savings potential. The most precise analysis looks at hourly conditions throughout a typical weather year. A number of computer programs are available to perform these complex calculations with site-specific information about both daylight conditions and energy costs. These programs are described in 4.4.2 – Daylighting Design Analysis Tools.

The energy savings from lighting control strategies are highly dependent on the specific application, especially in regard to the base-case assumptions. That is, the amount of energy that would be used in the absence of controls must first be either measured or estimated before the energy savings can be calculated. Some studies indicate that between the hours of 6:00 AM and 6:00 PM, daylighting controls can save 30% to 40% of perimeter lighting energy in a typical office space with vertical windows. During the summer, the energy savings can be much larger (over 50%), especially if the dimming system can dim efficiently over a wide range of light levels. Skylight applications can achieve even greater savings of 65% or more, if they provide high, even illumination levels across large interior spaces. Table 8-4 in section 8.1.4 compares the energy savings of a variety of controls and space types.

8.4.6 Documented Examples of Energy Savings from Daylight Dimming Systems

Although daylight switching schemes have become routine in many retail and warehouse skylight applications over the last decade, dimming systems, especially for sidelit applications, are less well understood. The energy savings potential of these devices is now being documented in realistic field studies. The results of four of these studies are summarized here.

Wal-Mart Store

Skylights with dimming control: One-half of Wal-Mart's 122,000-ft² Lawrence, Kansas, retail store has 64 skylights constituting 3.4% of that half's roof area. Electric lighting is provided by pendant-mounted direct-indirect luminaires with T-8 lamps and dimming electronic ballasts, for a total of 1.0 W/ft². During the day, two photocells, mounted in two of the skylight wells, dim all the lights in the skylit portion of the store. At night, a programmable time clock dims lights to 50% at 15 minutes before closing, and to 25% at closing (with the provision for an override by management for cleaning shifts and other special circumstances).

Power monitoring at this store demonstrated 47% lighting savings during the day in the daylit half of the store, and over 50% average nighttime lighting reduction. These energy savings are in addition to the substantial increase in retail sales noted in the skylit portion of the store as compared to other stores and to the non skylit portions of this store (Rundquist et al. 1996, p 109).

San Francisco Federal Building

Sidelighting with dimming control: In this extensively monitored (Jennings et al. 2000), sidelit office building, the energy savings were evaluated from a retrofitted perimeter daylight-dimming scheme. The conventional building envelope has single-glazed windows running from 3 ft above the floor up to the dropped ceiling. Each window has miniblinds to block direct sun and glare; and all but the north-facing windows have been retrofitted with solar film, reducing visible light transmission to about 40%. Electric lighting consists of 3-lamp, recessed parabolic luminaires with T-8 lamps and electronic ballasts. The open-plan office areas on the north and south sides of the third floor were retrofitted with dimming ballasts, controlled by ceiling-mounted photocells viewing out the vertical windows.

A half year's monitoring data for the daylight-linked control areas showed annual energy savings of 41% and 30% for the outer rows of lights on the south and north sides of the building, respectively. For the second row of lights, energy savings dropped to 22% and 16% (for the south and north respectively). This test installation shows that substantial energy savings are available from daylight dimming in sidelit applications and supports the retrofit of dimming systems in existing open plan office buildings. (See section 8.3.6 for more information about this study.)

Ralph's Grocery Store

Skylights with multilevel switching control: Ralph's Grocery in Valencia, California, has a central daylit core with a 20-ft-high ceiling that covers approximately 50% of the store's area. Forty-five rectangular 4 ft x 8 ft skylights provide daylight throughout the core area. Visible light transmittance for each skylight is 72% with a 66% shading coefficient, providing a combination of high natural light with low heat gain.

Three-lamp fluorescent luminaires in this core area are controlled by a three-level switching scheme (100%, 66% and 33%). When illumination levels reach 120 fc, the middle lamp in each luminaire is turned off. At about 140 fc, the two outer lamps turn off while the middle lamp restarts. All three lamps are never off simultaneously. A single low-cost photosensor controls the switching sequence and is located on a column inside the store, above the product casework. It communicates light levels to a central energy management system (which also controls the HVAC system) that switches the lights accordingly.

Based on short-term monitoring conducted by Pacific Gas & Electric during the summer of 1998, annual energy savings are estimated at 30% of the core lighting energy during daylight hours, or 2.0 kWh/ft²/yr. Because the central energy management system (EMS) eliminates the need for a dedicated controller, and a single photocell controls lights in the entire core area, Ralph's achieved a payback of under three years for these daylighting controls (Pacific Gas & Electric Company 1999).

Figure 8-27 – 3-level Switching at Ralph's Grocery Store
This 3-level switching scheme saves 30% of core lighting energy annually.

California State Automobile Association (CSAA)

Skylights with dim-to-off control: This single-story office building uses skylights with large splayed light wells to deliver ambient daylight across interior work areas. Ceilings in the center of the building are vaulted to 15 ft while the perimeter is at 10 ft. Twenty-nine triple-pane, low glare skylights spaced about 20 ft on center represent 3.7% of the floor area. Louvers at the top of the skylight wells are photocell controlled to maintain glare-free daylight illumination at about 70 fc. Electric lighting is provided by T-8 lamps with dimming electronic ballasts in recessed parabolic luminaires for a lighting power density of 0.66 W/ft². Eighty-six percent of the building's interior electric lighting is under daylight control. Continuous dimming reduces light output from 100% to 20% as daylight increases. When daylight illumination exceeds 60 fc, the electric lighting shuts off. Vertical windows at the perimeter provide low-glare views through perforated window blinds. DOE2 energy simulations were used to optimize the building design for minimum energy consumption.

Extensive monitoring of this building demonstrated a reduction in annual lighting energy of 32%. The daylighting features saved additional money by reducing kW demand and HVAC equipment costs (Pacific Gas and Electric Company 1999).

Figure 8-28 – Dimming Fluorescent Luminaires at CSAA
Skylights with dim-to-off controls save 32% of electric lighting energy in this office building.

8.4.7 Costs

The additional costs of a daylighting control system result from:

- The control hardware, which includes the cost of photocells and control modules;
- Additional wiring, which includes the cost of wire (usually low voltage) and installation labor;
- Incremental ballast costs, which include the incremental cost of dimming ballasts for dimming systems and tandem wiring for switching systems; and

- Commissioning and maintenance costs, which include costs to initially calibrate and verify the system, plus ongoing costs for photocell cleaning and recalibration, and labor for burning in dimming fluorescent lamps after relamping.

8.5 Building-level Controls

Most of the systems described in sections 8.2 (Switches and Dimmers), 8.3 (Occupancy Sensors) and 8.4 (Daylighting Controls) can be installed and operated at the local level. With occupancy sensors, the sensor and the switching controls are located in the same space. With daylighting controls as well, the light sensor is usually located in the space where the electric lighting is controlled. The same is true of personal controls, where the individual dims the lights in his or her own local area. Each of these systems can operate in isolation of one another and don't require global information about the facility to function properly.

Some lighting control strategies, however, must be applied at the building level to be effective. Building-level controls, also called energy management systems (EMS) or building automation systems (BAS), are used to implement strategies such as scheduling and advanced load management. This section discusses:

- Energy management systems that schedule lighting operation throughout a complex;
- Integrated lighting and building services that take advantage of load shedding and real-time pricing to reduce building energy costs;
- Protocols that allow control networks to talk to one another; and
- Examples of different building-level controls.

8.5.1 EMS Systems

What is an EMS System?

An energy management system (EMS) is a *multi*processor control system that controls most or all of a facility's building equipment loads. Most building EMS's are able to control many (typically hundreds) of electric loads in a building, such as motors and HVAC equipment. These systems are very good for controlling many switching loads throughout a facility and for coordinating their day-to-day operation. Each switch is considered “one control point.” Systems are usually priced by the number of control points.

Since lighting systems are also loads in a building, many manufacturers have developed systems that manage energy functions for lighting systems. These lighting management systems (LMS) typically have similar capabilities to energy management systems, although their specific function is optimized for the operation of a large number of smaller lighting loads. With an EMS, or lighting management system, all the loads within a facility can be controlled from a central location. Nowadays, a building EMS will be attached to the facility’s existing information technology (IT) network.

Some Commissioning Required

For these controls to be effective at managing energy usage, the facilities’ operation group must play a significant role in commissioning the EMS system upon installation. Commissioning in this context refers to understanding the program and use of each space within the complex, and properly entering in the stop and start times for all the loads within the facility to be controlled. Obviously this requires knowledge about how the different spaces are going to be used. If the use of the space is well known, and the EMS is properly commissioned, the lighting system in the building can be made to operate extremely efficiently. However, without this knowledge, commissioning will not be done properly, and it is likely that operation will be compromised.

Dimming Control

One disadvantage of many EMS systems and some lighting management systems is that they have generally not been designed to control many dimmable lighting circuits. Most automatic lighting control functions are best accomplished with dimming, so an EMS or LMS that lacks the ability to control multiple dimming zones is a drawback. Most of the EMS outputs are on/off control only, and do not lend themselves to the control of multiple dimmable loads.

Systems are now becoming available that combine on-off control of lighting circuits and the ability to control multiple dimming channels. Some systems consist of lighting field panels that are distributed throughout a facility and tied together via a local-area network (LAN).

8.5.2 Scheduling Using EMS

With scheduling, a lighting control strategy best implemented by using building-level controls, lighting loads throughout a facility are turned on and off at appropriate times. The primary function of scheduling controls is to turn off lighting loads when the space is expected to be unoccupied (also called "sweep-off" control since lighting circuits are swept off at scheduled times).

Scheduling works well for large spaces where occupancy is predictable. For smaller zones and zones where occupancy patterns cannot be predicted ahead of time, occupancy sensors are a better solution. In large buildings (over 50,000 ft²), scheduling is typically implemented using EMS-type systems that are designed for large multizone building control. For small commercial buildings, there are compact programmable relay panel controls. In both large and small buildings, scheduling is typically implemented using latchable relays that are installed at the lighting circuit breaker panels.

The controllable relays are usually connected in series with the existing branch circuit wiring, which results in on/off control of entire lighting circuits. Since most lighting circuits in buildings are typically 30 amp breakers, each circuit breaker may control lighting power for between 2000–5000 ft² of lighting. Thus scheduling implemented with relays and lighting circuit breaker panels usually results in on/off control over large banks of lights. For new construction, it may be economical to apply the relays at a smaller level, that is, at the switch leg level. This provides a finer degree of control over the building lighting, but has greater installation costs because of the increased number of control points.

"Sweep-off" Control

Scheduling is a requirement of California's Title 24 (Energy Efficiency Standards for Residential and Nonresidential Buildings). Scheduling is also mandated in the ASHRAE Standard 90.1–1999 building standard for large buildings. Figure 8-29 and Figure 8-30 show how scheduling might be applied in large commercial buildings as required by Title 24 and ASHRAE Standard 90.1–1999.

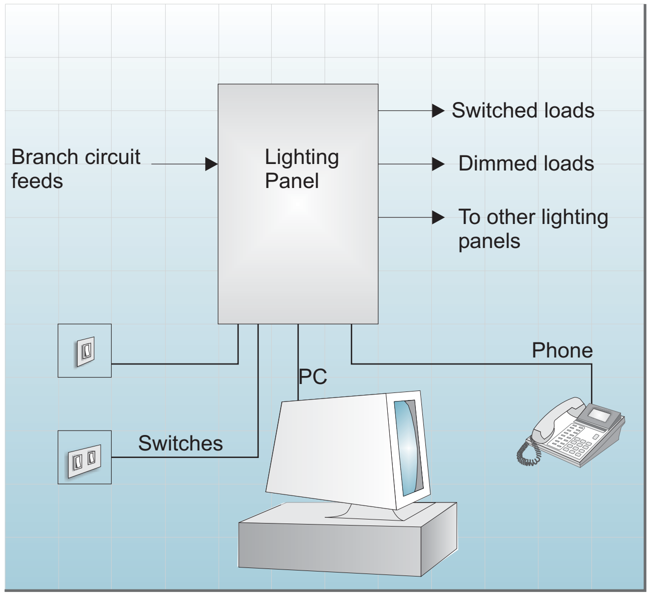


Figure 8-29 – Circuit Diagram for EMS-Based Scheduling, Large Building

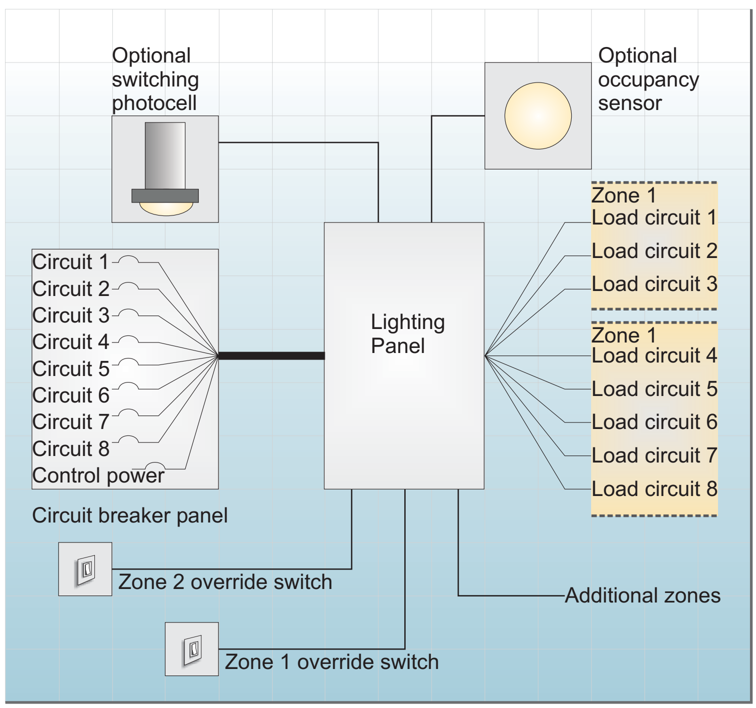


Figure 8-30 – Circuit Diagram for EMS-Based Scheduling, Small Building

Overrides

No matter how well known the occupancy patterns for a facility's different spaces are, the ability to override the automatically imposed lighting schedule must be addressed. These overrides are usually applied in one of four ways: (1) low-voltage switches, (2) latching momentary switches, (3) telephone override systems, or (4) intelligent line voltage switches. Sometimes a combination of these methods is appropriate for buildings with heterogeneous usage.

Low-voltage Switches

Low-voltage switches can be installed at convenient locations within each building space to allow the lights to be overridden by occupants when necessary. Since these switches are low voltage (24 volts), their electrical requirements are not as strict as the requirements for high-voltage switches. Because of their lower cost, it's possible to use as many low-voltage switches as are necessary to assure smooth building operation. These switches must be easily accessible by the occupants within the space, especially if they are the only way for occupants to override the lighting schedule. A good rule of thumb is that the low-voltage switch that controls the lighting in a given area should be immediately visible by an occupant anywhere within that building space.

Latching Switches and Intelligent Line Voltage Switches

A latching switch appears to be just like a regular on/off wall switch but it has one significant difference: it will turn off its connected load when the power to that switch is interrupted for approximately five seconds. Once the latching switch switches off its load, it will not restore lighting until it is switched back on again manually. By using controllable relays in the lighting circuit breaker panels to provide large block lighting scheduling control, and using latching switches in each of the individual controlled spaces within that larger block, an effective override system can be provided.

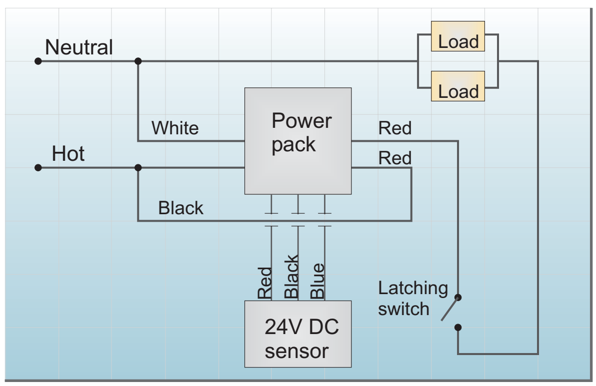


Figure 8-31 – Latching Switch with Wiring Diagram

Should an occupant in one of the spaces need to restore their lights, they would walk over to their latching switch and turn their lights on again. The lighting in this smaller zone would not be turned off again until either the occupant turned it off or it was again switched off using the programmable relay. Because there is a possibility that the occupant may need to find the latching switch in near darkness, these latching switches are often self illuminated. The combination of programmable relays in the circuit breaker panels and latching switches as overrides forms a cost-effective scheduling and override system for many building applications.

Telephone

With a telephone override system, the existing telephone circuits are used to turn lights back on after the scheduling system has turned them off. The system works as follows: the lights are turned on and off according to expected occupancy. Should people be working after the lights have been switched off, they would access their lights by punching a number on their phone's touchpad. Telephone override systems are a relatively inexpensive way to provide local occupant control of lighting, and are fairly robust and reliable. On the other hand, some occupants have an aversion to using a telephone to control their lights.

Overriding the Overrides

All scheduling systems provide some capability to override any existing overrides at particular times. This can be important, because overrides of lighting systems often result in wasting significant energy. If lighting overrides are not themselves overridden, lights may stay on needlessly. California's Title 24 requires that overrides by swept off every two hours. This may be too long for some facilities.

Commissioning

As discussed in section 8.1.6, it is critical that scheduling systems be properly commissioned upon installation. Installation generally consists of inputting the start and stop times for each of the independently controlled zones within the facility. If the commissioning is done prior to occupancy, it may be necessary to adjust the start and stop times once the facility is fully occupied. For example, if some zones are frequently overridden after the lights are scheduled to be off, it may be appropriate to extend the lighting schedule so that the lights switch off later. This will reduce the frequency of overrides. In other areas, the anticipated occupancy may not correlate with the actual occupancy of the space. Again, the start and stop times in these zones should be adjusted to accommodate the local occupancy patterns. Another aspect of commissioning is to alert the building occupants to the location and function of the overrides. A well-operated scheduling system, however, should not require frequent overriding.

8.5.3 Building Controls Integration

There are many benefits to integrating the operation of the building lighting with other electrical loads in a building, especially if the overhead lighting is dimmable. Even in facilities without dimmable lighting systems, there are economies from combining switching control of lighting circuits with other building electric loads. Scheduling controls require commissioning the operation of many lighting zones in a complex, and this is best accomplished from one facility. If a building's lighting system consists of multiple dimmable lighting zones that can be controlled from an authorized computer, the facilities manager can have near-immediate control of electric demand throughout a facility. As lighting averages 37% of a typical commercial building's total electrical demand (Energy Information Administration 1996), reducing power to a building's dimmable lighting system by 25% (hardly noticeable in terms of light output) would reduce a building's electric demand by 10%. With dimmable lighting, it is even possible to adjust lighting power according to the hourly price of energy or other utility pricing signal.

Legacy Building Control Networks

Over half of U.S. commercial buildings over 50,000 ft² have some building automation system (Energy Information Administration 1995). Given that buildings of 50,000 ft² or greater constitute some 33% of all U.S. commercial-building floor space, this means that some 11 billion ft² of floor space are controlled by a BAS. Most of these systems, it is reasonable to suppose, may be older "legacy" systems that are based on proprietary software architectures no longer receiving much support. Even though these systems are slowly being phased out, any practical building automation solution must address the issue of legacy networks.

Protocols

Integrating lighting control with other building equipment requires consideration of the protocols used to allow communications between control products from different equipment vendors. The development and acceptance of open-protocol communications standards for building equipment controls and the pervasiveness of the Internet is creating new opportunities for building owners and operators. BACnet (Building Automation Communications network) is an open-protocol standard (ASHRAE/ANSI standard) for intermediating BAS transactions, as is LonMark, which is based on LonWorks from the Echelon Corp. Both protocols integrate control networks from different vendors with the Internet. Both protocols use the Internet (or TCP/IP) as the communications medium between control networks. Most modern buildings already have wiring to support their computer networks; this "road" serves as well for building equipment communications as it does for enterprise computing. Comparisons between LonMark and BACnet are beyond the scope of these guidelines, but any modern building using BAS controls will probably elect to use a hybrid system with some equipment running LonMark and other control networks running BACnet (see Figure 8-32). Gateways between LonMark and BACnet are straightforward.

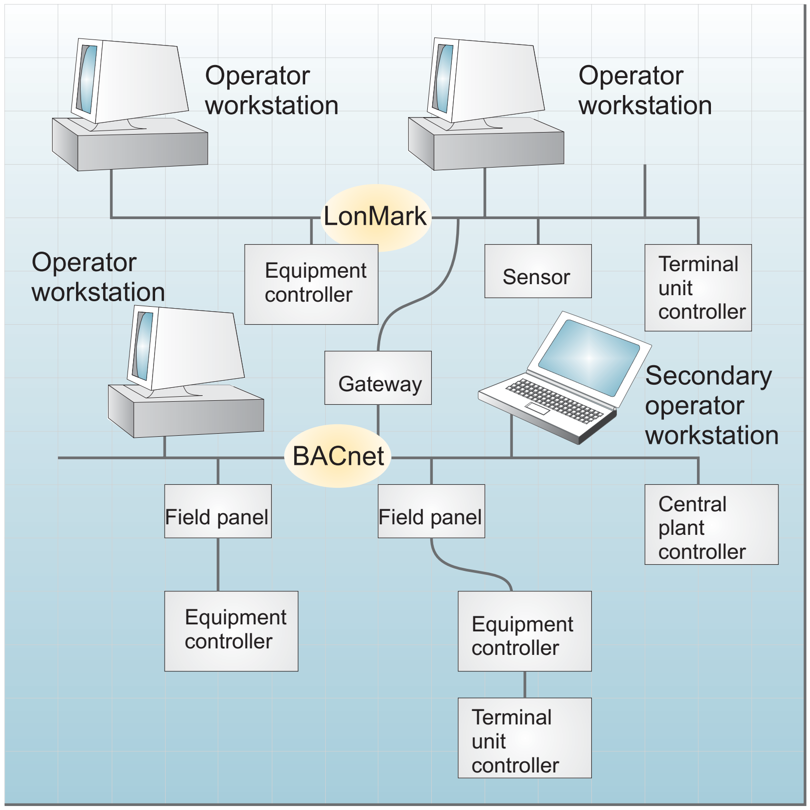


Figure 8-32 – Control Network Running LonMark and BACnet

8.5.4 Load Shedding

Load shedding is a technique for selectively dropping building electrical demand either to reduce peak demand charges or avoid a brownout condition in the service district (see sections 3.1.4 and 8.1.5 for general information about load shedding). The successful use of building-level lighting controls for load shedding requires: (1) that a majority of the lighting systems be dimmable and controllable; (2) knowledge of the facility's instantaneous aggregate electric demand; and (3) appropriate software tools to process the demand data and utility pricing signals to manipulate lighting power levels according to the facility's economic needs or the system's power requirements.

Knowing the facility's instantaneous building-wide electric demand is key to advanced load management, since one portion of the cost of electricity is usually related to this instantaneous demand. Increasingly, this information will be available on the Internet using smart-metering technology. In addition to knowing the electric demand, it is necessary to identify the appropriate lighting zones for load shedding, and to know when, by how much, how quickly and how long the curtailment will take place. This requires robust software that can automatically make appropriate changes quickly. Increasingly these services may be offered by energy service companies that supply lighting services (along with other building services) for an annual fee.

8.5.5 Real-time Pricing

A related load-management strategy is to use power price and availability (or reliability) forecasts to decide which lighting services should be curtailed when and by how much according to the severity of the situation. With deregulation, the cost of electric energy will be allowed to fluctuate more throughout the day; on severe peaking days, energy prices can spike for short times. Institutions with pricing arrangements with their energy service provider might voluntarily elect to significantly curtail lighting loads for short periods of time on specific days to avoid buying energy when its cost is much higher. Obviously, this requires information as to exactly how much electric energy is going to cost throughout the day. As utilities scramble to offer new incentives to retain customers and attract new ones, more institutions may be taking advantage of real-time pricing to reduce operating costs of buildings or building complexes.

8.6 Other Strategies and Integrated Controls

8.6.1 Adaptive Compensation

Adaptive compensation is a lighting control strategy for improving lighting quality and saving energy at night. The strategy takes advantage of the fact that the human visual system tends to need and prefers less illumination at night than it does during the day. An installation using adaptive compensation such as a shopping mall, airport concourse or supermarket would dim overhead lights during the evening hours, thus both reducing light levels to a preferred level and saving energy. Because it is generally desirable that changes in light levels in occupied spaces be done gradually, adaptive compensation is best implemented with dimming hardware. Adaptive compensation should only be used in facilities that operate outside of regular daylight hours, and in applications where reductions in electric lighting level are acceptable. Consequently, adaptive compensation should not be used in installations where visual tasks are critical or where concerns about alertness argue for higher nighttime lighting levels. (See chapter 2 for information about human vision under nighttime conditions.)

Implementation

Dimmable fluorescent or HID lighting could be used with an adaptive compensation strategy. However, if HID sources are dimmed, there may be shifts in color temperature and apparent color of the lighting that are undesirable in more sensitive applications, especially when the light source is heavily dimmed (section 6.6 discusses HID sources). Multilevel or even hi-lo stepped control may be adequate for adaptive compensation.

Because adaptive compensation saves energy in the evenings, it can be implemented using either photocontrols or time-of-day controls. Photocell control is probably best, since this can easily keep track of changes in day length as the year changes. However, time-of-day controls are acceptable if properly commissioned.

The easiest way to implement adaptive compensation is to use an externally located photoswitch. When the photoswitch detects that the daylight has dropped below a threshold level, a contact closure occurs, and the controller then lowers the electric lighting to a preset level. The light level reduction that takes place at this time will depend upon the application. For many applications, it may be possible to reduce light levels and accordingly lighting power, by about 50% compared to full-up operation. For installations with significant number of hours of evening operation, this can result in considerable energy savings.

Adaptive Compensation Examples

Supermarket: Many supermarkets operate 24 hours a day. Adaptive compensation can be effectively applied in these applications by running the lights at lower intensity for evening operation than during the day. The light levels that are required in a supermarket during the daylight hours are fairly high. With adaptive compensation, the light levels provided at night would be cut in half with a commensurate energy savings.

Airport Concourse: In airports, both concourse and waiting room lighting can be dimmed effectively with adaptive compensation, since most airports, like supermarkets, have 24-hour a day operation. Furthermore, in many airports, there are extensive windows that provide cues to the passengers and operating personnel as to whether or not it is light or dark outside. In airports, lighting can be dimmed to at least 50% during the evenings, both in the concourse area and in waiting rooms.

8.6.2 Integrated Controls

With integrated controls, more than one lighting control strategy is implemented at a time with the same lighting hardware. For example, integrated controls for an office application might exploit daylighting, tuning, and scheduling all with the same hardware.

By combining more than one strategy, more energy can potentially be saved and the greatest economic benefit extracted from the investment in controls. Combining several strategies increases the economic benefits if the marginal cost of adding additional strategies onto one base strategy is small. While integrated controls offer the potential of greater energy savings and more highly responsive lighting systems, they also run the risks inherent in any complex system: more complexity in design and more difficulty in diagnosing failure. These trade-offs should be carefully considered in the design of a system.

Implementation

There are two ways to implement integrated controls. The first method relies on assembling discrete components to form systems capable of executing more than one strategy. The second method uses multifunction controllers that may take inputs from several different sensors, including light sensors, occupancy sensors, and signals from energy management systems. Multifunction controllers represent state of the art in lighting controls.

Systems from Discrete Components

By carefully selecting, specifying and assembling components to function together as systems, a knowledgeable specifier can design a lighting control system that exploits more than one strategy. A simple example of this is the combination of occupant-sensing controls and daylight controls in an office. Figure 8-33 shows how the different lighting control components would be wired together into the building's electrical system to provide both occupancy-based and light-sensing-based control. In this application, the photocell is connected to the low-voltage control that ties together the different ballasts serving the control zone, while the occupancy sensor merely interrupts the high-voltage power going to the lighting system.

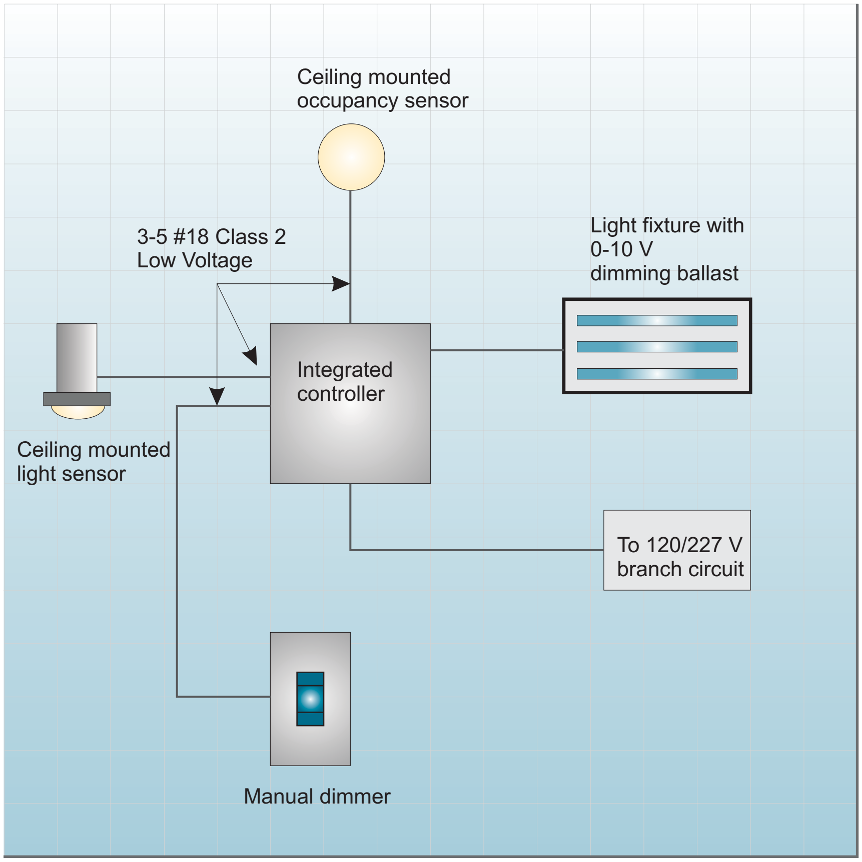


Figure 8-33 – Wiring for Combination Occupancy Sensing and Daylighting Controls
This figure illustrates how different lighting components could be wired to provide both occupancy sensing and daylighting in a typical small office application.

Another example of integrated lighting controls using discrete components is the combination of daylight-sensing and manual-dimming controls. In this application, both the manual dimmer and the photocell are tied in parallel to the low-voltage control wiring.

A third example of integrated controls using discrete components is the combination of manual dimming with occupancy sensing. At least one manufacturer has a wall-box-mounted occupancy sensor that also has a dimming control for the electric lights. This type of control may work very well in high-end office applications, where it is desirable to reduce lighting hours during unoccupied times using the occupancy sensor, but also to provide the building occupant with a means to control light levels in their individual space.

Multifunction Controllers

If more than one strategy is to be used in an application, consider using a multifunction controller to coordinate all the control functions. With a multifunction controller, the high-voltage wiring going to the lighting system as well as all the sensor inputs, such as a photosensor, wall-box controller, occupancy sensor and tuning controls, all go to one box. This box or controller contains all the intelligence necessary to process the multiple sensor inputs, and to control light levels accordingly.

The main advantage of the multifunction controller is that all commissioning adjustments can be centralized in one accessible location, which greatly increases the probability that commissioning will be done correctly. A well-designed multifunction controller will be able to resolve apparently conflicting inputs from the different sensors, and provide the correct light level given the different environmental conditions. For example, if a photosensor and an occupancy sensor are tied to a multifunction controller, the controller would know to keep the lights off if the space were unoccupied, even if there were insufficient daylight as detected by the photosensor. Most multifunction controllers are designed so that the input that results in an action requiring the least amount of lighting energy wins. Multifunction controllers, however, are more expensive than using multifunction controls with discrete components.

9. APPENDIX

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9.2 Acronyms

Here is a list of acronyms for organizations, government agencies and legislation used in the *Advanced Lighting Guidelines.*

Acronym	Organization
ADA	Americans with Disabilities Act
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CEC	California Energy Commission
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CIE	International Commission on Illumination
DOE	United States Department of Energy
EIA	Energy Information Administration
EPA	United States Environmental Protection Agency
EPAct	Energy Policy Act of 1992
EPRI	Electric Power Research Institute
FDA	United States Food and Drug Administration
FEMP	Federal Energy Management Program
IAI	International Alliance for Interoperability
IALD	International Association of Lighting Designers
IDA	International Dark-Sky Association
IEC	International Electrotechnical Commission
IESNA	Illuminating Engineering Society of North America
IFC	Industry Foundation Classes
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
NCQLP	National Council on Qualifications for the Lighting Professions
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NFRC	National Fenestration Rating Council
NLPIP	National Lighting Product Information Program
NOM	Normas Officiales Mexicanas (Mexican product certification standards)
NREL	National Renewable Energy Laboratory
PSIC	Passive Solar Industries Council
UBC	Universal Building Code
UL	Underwriters Laboratories

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