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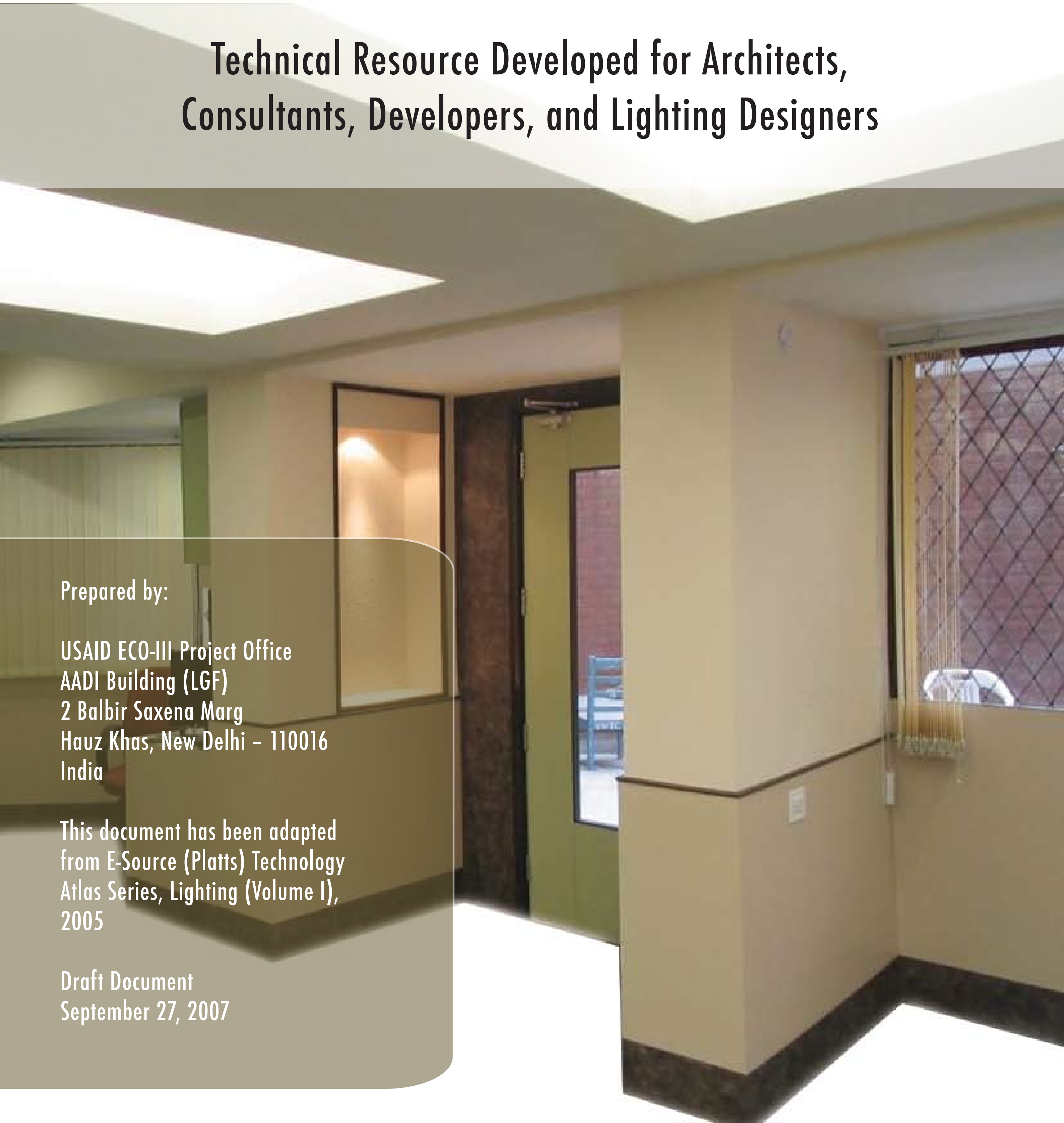
LIGHTING DESIGN and TIPS FOR ECBC COMPLIANCE



Technical Resource Developed for Architects, Consultants, Developers, and Lighting Designers

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1 ACKNOWLEDGMENT

The 'Lighting Design and Tips for ECBC Compliance' is adapted from *E-Source (Platts) Technology Atlas Series, Lighting (Volume I), 2005.* A considerable emphasis is given on different types of Lighting Systems and its design. A section is devoted for existing and upcoming energy efficient lighting technologies. This guide is prepared by ECO-III project to create understanding among lighting professionals and building lighting industry people as well.

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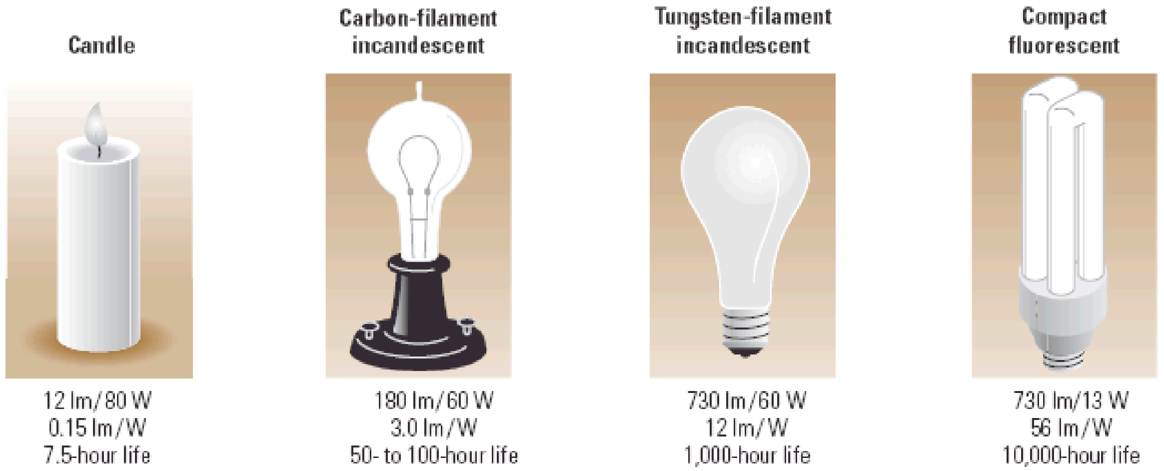
2 INTRODUCTION TO LIGHTING SYSTEMS

Lighting technology has a rich history of evolution, and the pace of change and innovation has accelerated in recent years. Just when it seems we've exhausted all the possibilities, along comes a new technology that lasts longer or performs better or costs less than what we currently think is state of the art. The potential payoff is so great that it makes sense to keep abreast of the latest developments.

To gain some perspective on how far we've come, consider the following description, from a 1980 lecture, of the astonishing progress in the efficiency of lighting technology since the ordinary candle: a source which, though a great advance over the open fire, consumed about 80 watts of chemical energy to emit only 12 lumens (lm) of light.12 The quotient of these two values, the candle's "efficacy," was only 0.15 lm/watt. In a mere seven hours' burning, too, the candle went up in smoke. The candle was succeeded by various kerosene, oil, and gas lights, and ultimately by the early electric light—the carbon-filament incandescent lamp. This used one-quarter less energy (60 watts of electricity), emitted 15 times as much light (180 lm), hence had an efficacy 20 times higher (3 lm/watt), and lasted about 10 times as long (50 to 100 hours) as the candle. Next came another quadrupling of efficacy, via the modern tungsten-filament incandescent lamp, with 60-watt input, 730-lm output, 12-lm/watt efficacy, and 1,000- hour nominal life. The tungsten-filament lamp reduced the cost of lighting services by nearly 600-fold relative to the candle, while markedly improving reliability, convenience, and lighting quality and eliminating the fire hazard represented by the candle. One tungsten-filament lamp could match the lifetime lumen-hour output of 8,100-odd candles, to say nothing of the cost of matches and replacement labor; yet that lamp and its electricity cost only about as much as 14 candles. The lamp provided 80 times as much light per unit of energy as a candle did—a combined gain of more than 10,000-fold in lumen-hours delivered per watt and per lighting source lifetime. Technology didn't stop there, however. The modern mix of incandescent, fluorescent, and high-intensity discharge lamps in a country like the United States

The compact fluorescent lamp has improved the product of efficacy and lifetime 50-fold compared with the tungsten-filament lamp and by half a million compared with the candle.



Notes: lm = lumen; W = watt.

Source: Platts

averages about 50 lm/watt[13]—nearly four times the efficacy of tungsten-filament incandescent lamps—and has an average lifetime probably in the vicinity of 12,000 hours. Thus the diversification of lighting sources during the past few decades has increased the mathematical product of efficacy and lifetime by a further factor of about 50 compared with the tungstenfilament lamp, or by roughly half a million altogether since the candle figure above.

3 DAY LIGHTING

Sunlight is free and uses no electricity. Human beings are designed to live in sunlight. Although our optical sensors (eyes) can see only a very narrow portion of the electromagnetic spectrum, they are well adapted to the light from our neighboring star, and we can see over 50 percent of the wavelengths the sun emits. Both economics and the imperatives of health and aesthetics favor the practical use of daylighting in buildings.

- Daylighting is both an art and a science. The key is to admit only as much light as necessary and to distribute it evenly and without glare. Poorly designed daylighting can be worse than none.
- Daylighting is applicable in both clear and cloudy climates. In fact, many designs work best under overcast skies.
- Daylight-sensitive dimming controls for electric lights can yield substantial savings in energy and peak lighting demand.
- Because sunlight produces less heat per unit of light than typical electric lights, properly designed daylighting can reduce cooling loads.
- Several glazing options for improved daylighting design now exist, and more advanced products are under development. Spectrally selective tints or coatings — including advanced retrofit films—reduce heat gain but allow good visible transmissivity. Other systems, such as light shelves and prismatic panels, help reduce glare and heat gain and improve the uniformity of illumination. More advanced systems, such as holographic diffracting elements, are under development and may enable better control of incoming daylight.

3.1 DAYLIGHTING DESIGN APPROACHES

Common daylighting design elements include ordinary façade windows, elements such as atria and U-shaped buildings that increase exposure to the sun, clerestories, roof monitors (fenestration raised above the roof plane, rather than parallel to it), skylights, and stepped-back building forms (which avoid the “urban canyon” effect, where buildings are in shadows most of the day). Much of the art of practical daylighting lies in the use of light shelves, wide windowsills, special reflectors, louvers, walls, blinds, and other design elements that bounce light deep into the building. These methods also avoid the glare and the strong modulation (intense light near the window, rapidly falling off with increasing depth) of direct-beam daylighting. Bi- or multilateral daylighting is much preferred over light from only one direction. Interior and exterior foliage can also be used to control light, temperature, humidity, views, privacy, and aesthetics.

3.2 ENERGY SAVINGS AND DEMAND REDUCTION

Designers, engineers, utility companies, and building energy standards are increasingly recognizing daylighting as a potential source for energy savings. Using the free light from the sun and sky for interior illumination reduces the need for electric lighting in daylit areas.

Because up to 70 percent of the usable space and installed lighting capacity of many commercial buildings is in the perimeter zone, daylighting has a greater potential to reduce energy and peak demand than is commonly recognized—even in conventional buildings. Depending on whether the photosensitive controls dim the lamps in steps (to, say, 50 or 30 percent of full output), continuously dim the lamps (down to 5 percent output), or turn them off completely when some threshold of daylight is available, the lighting energy savings of daylit spaces often range from 40 to 60 percent when averaged over the entire year. Because daylight is readily available during hot summer afternoons, the peak demand benefits of daylighting controls are typically greater in percentage terms than the energy savings. Designing for daylighting can also result in a reduced cooling load for the building. All of the energy used for lighting eventually becomes heat, which adds significantly to the internal heat gains of a building. Because the luminous efficacy of daylight—from a clear or an overcast sky—is significantly higher than that of most common types of electric light, daylight contributes less heat to a space per given amount of light (Figure). Design expertise is required to ensure that daylight is diffused adequately and in a relatively even manner throughout the space. Selecting a glazing that maximizes light transmission and minimizes total solar transmission can further reduce the heat gains resulting from daylight penetration.

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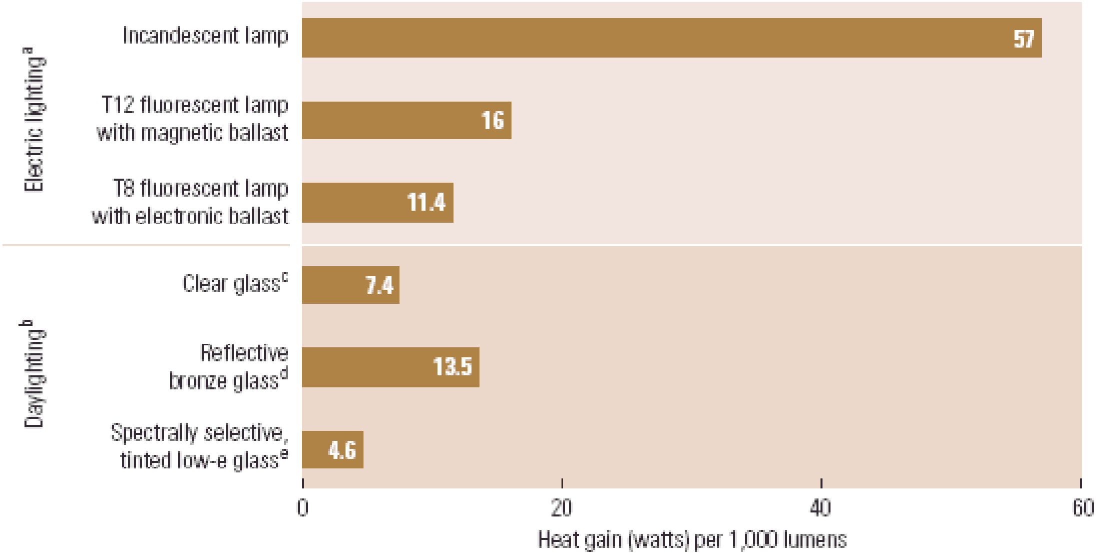

Figure 5-4: Building heat gain from different sources of light[1]

With proper glazing selection in a building, daylight will contribute far less heat per unit of light delivered to the interior than electric lights do.

Notes:

a. Assumes luminous efficacies of 17.5 lumens per watt (lm/W), 62 lm/W, and 88 lm/W, respectively, for the electric lighting options.

b. Assumes 125 lm/W efficacy for daylighting.

c. Visible transmittance (VLT) = 0.82, shading coefficient (SC) = 0.90, solar heat gain coefficient (SHGC) = 0.78, and relative heat gain = 188 Btu per hour per square foot (Btu/h/ft2).

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[1] Source: Platts; data from Claude L. Robbins and LBNL's WINDOW 4.0 [6]

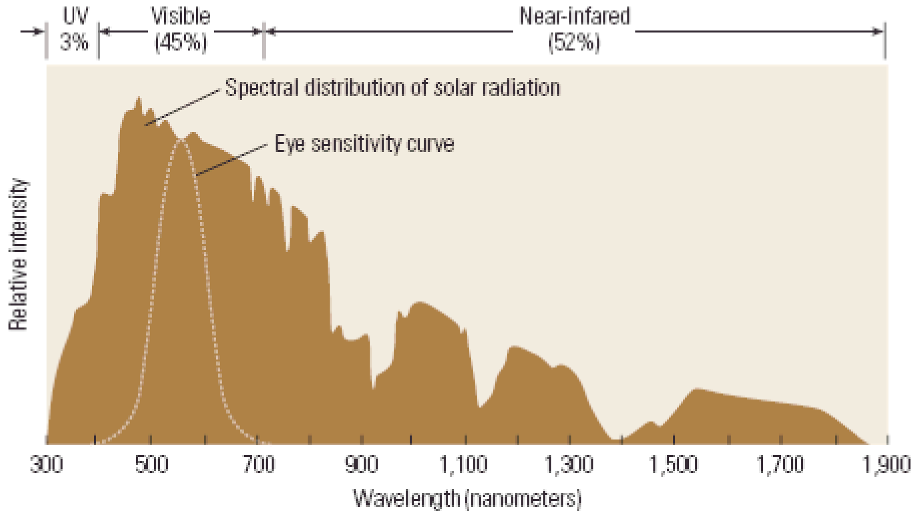
d. VLT = 0.20, SC = 0.38, SHGC = 0.33, and relative heat gain = 84 Btu/h/ft2.

e. VLT = 0.40, SC = 0.26, SHGC = 0.23, and relative heat gain = 57 Btu/h/ft2.

3.3 GLAZING SELECTION

Glazing should be selected with consideration for daylighting goals as well as the building's heating and cooling requirements. Most large commercial buildings' loads are dominated by cooling, so glazing that transmits adequate light for the daylighting application and minimizes solar heat transmission is usually best. In buildings dominated by heating loads, glazing should be carefully chosen to minimize heat loss and, in some cases, it should be configured to increase passive solar heat gain, while maximizing daylighting. Horizontal skylights are particularly susceptible to heat loss as well as direct solar gain, so they should be chosen discriminately for daylighting applications. About half of the sun's energy is visible to the human eye, while the other half (longer-wavelength near-infrared or shorter-wavelength ultraviolet) is invisible—contributing only heat to the building interior. To reduce cooling load, the ideal window would transmit as much of the visible portion of the sun's energy as is desired for the particular application, while rejecting the rest of the solar radiation. Glazing systems are rated using several parameters. The most common performance metric for rating total energy transmission is the solar heat gain coefficient (SHGC). SHGC is the fraction of the incident solar energy transmitted through a window. Windows with low SHGC values improve comfort for building occupants near sunlit windows, lower the total cooling load of the building, and help smooth out the difference in cooling loads between perimeter and core zones. The shading coefficient (SC), a similar metric, is the ratio of total solar transmittance to the transmittance through one-eighth of an inch of clear glass. The SC, which is being phased out as a glazing metric, is approximately equal to 1.15 times the SHGC. Taken to the extreme, a focus on reducing cooling loads by using glazing with the lowest possible SHGC or SC values would lead one to abandon windows altogether in favor of opaque wall systems. Obviously, the reason for having windows is to transfer light from the outside to the inside (and vice versa, in the case of retail display windows). Therefore, reductions in SHGC and SC must always be considered in conjunction with the corresponding reduction in visible transmittance (VLT)—the fraction of visible light transmitted through the window.

Transmittance is important not only for visibility but also when using daylighting to offset interior electric lighting loads and associated cooling loads. Reflective glass products with VLT values as low as 5 percent are common in many cooling-load-dominated regions. The windows are there for visual and economic reasons (glass is cheaper than masonry, insulation, and drywall), but the highly tinted glass creates such dim interiors that they need almost as much electric lighting as if the walls were opaque. Ironically, the electric lights then typically release more waste heat year round than the sun would deliver through normal windows. Therefore, the air conditioners must be sized to remove heat emitted by lights that wouldn't be needed during the day if the appropriate glazing were used.



Source: Platts

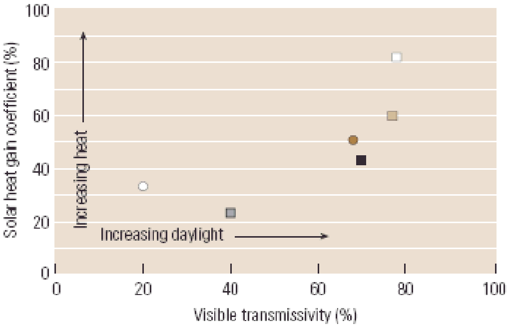
Figure 5-5: The solar spectrum

The ideal window will transmit visible light and block ultraviolet (UV) and near infrared radiation.

3.3.1 NON-ENERGY BENEFITS OF DAYLIGHTING

Daylighting benefits go beyond energy savings and power reduction. Daylight— the light source that most closely matches human visual response—is considered the best source of light for color rendering and improves people's ability to perform visual tasks. In another study, research conducted by the Lighting Research Center shows that the presence of windows appears to make office workers more productive.

Glazing	Visible	SHGC
Clear □	0.82	0.78
Low-e coating ▨	0.77	0.60
Dark reflective bronze tint ○	0.20	0.33
Spectrally selective green tint ●	0.68	0.51
Spectrally selective low-e (clear) ■	0.70	0.43
Spectrally selective low-e with green tint ▨	0.40	0.23



Source: Platts

Figure 5-6: Total solar and visible light transmissions for selected glazing units

Glazing units with high visible light transmission and low solar heat gain coefficients (SHGC, the fraction of the incident solar energy transmitted through a window) are best for daylighting in buildings dominated by cooling loads.

4 LIGHTING DESIGN TIPS

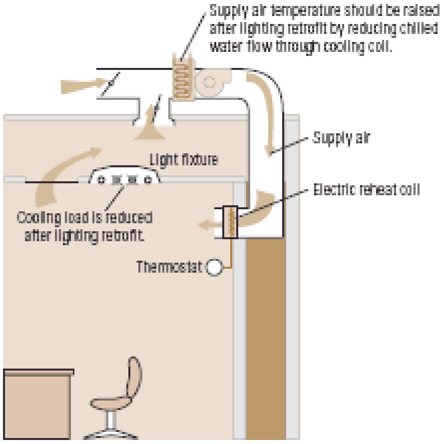
4.1 EFFECTS OF LIGHTING ON OTHER BUILDING SYSTEMS

Lighting influences other building systems in a variety of ways, ranging from changes in heating and cooling loads to effects on power quality.

4.1.1 INTERACTIONS WITH HEATING AND COOLING SYSTEMS

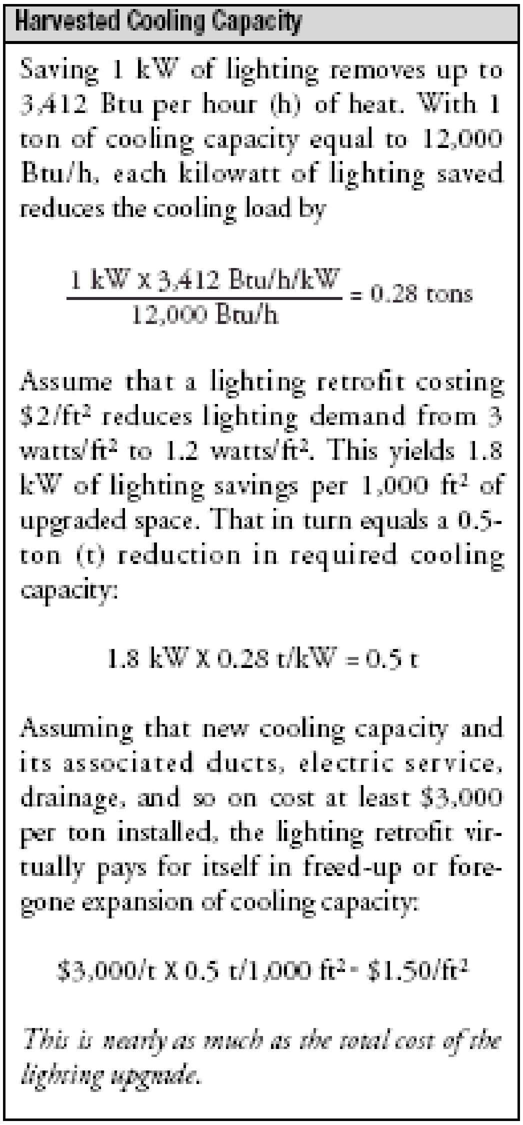
Except for the small percentage of light that escapes through windows, all energy used by interior lights ends up as heat inside the building. Although some of this heat may be picked up by the return air stream and directly exhausted, and a small fraction may be absorbed by the building mass and later released during unoccupied times, lighting typically constitutes the largest internal heat gain in commercial buildings. This internal heat gain is useful when the building requires heat, but it is unwanted when the building requires cooling. Energy-efficient lighting adds less heat to a space per unit of light output than inefficient lighting. The net effect on HVAC systems can be expressed in terms of annual site or source energy, peak kilowatt demand for cooling, required cooling capacity, energy bills, or environmental impacts. The net annual effect on site HVAC energy use depends on the type of building, the climate, the heating and cooling systems, and the relative size of the heating and air-conditioning loads. Large buildings that are dominated by internal loads and use far more air conditioning than heating can experience a site energy HVAC bonus of 40 percent or more. This means that each kilowatt-hour of reduction in annual lighting energy use yields an additional 0.4 kWh of annual reduction in HVAC energy by reducing cooling energy more than it increases required heating energy. For small, envelope-dominated buildings— especially those in cold climates—the net impact is often an HVAC penalty, meaning that each kilowatt-hour in lighting energy use increases HVAC energy by increasing the annual heating energy use more than it reduces cooling energy. The precise impact on any given building is best determined by computer simulation, although some simplified methods for approximating the effect are discussed below. Even if a building has an HVAC penalty in terms of annual site energy, it may experience a net reduction in energy bills, source energy, or pollutant emissions. If the building is heated with natural gas that costs a lot less for an equivalent amount of energy than the electricity used for cooling, a small reduction in cooling energy can save more money than a relatively larger increase in heating energy. Moreover, the fuel-to-delivered-electricity losses of the electric power system mean that each kilowatt-hour saved by the customer results in three to four units of source energy saved at the power plant. There is a correspondingly leveraged reduction in pollutant emissions—particularly if the power plant burns coal, which emits more pollution than natural gas. Thus, for example, a small commercial building in a cold climate that has a net site HVAC penalty of 25 percent might have a net economic HVAC bonus of 2 percent, a source energy bonus of 10 percent, and perhaps an even higher bonus in terms of reduced pollutant emissions.The reduction in summer peak cooling demand is often greater than the net HVAC energy bonus, if there is one. In a predecessor edition to this volume, Competitek used parametric simulations to determine the HVAC/lighting interactions for a 60,000- square-foot (ft2) office building and a 12,000-ft2 retail store in Austin, Texas. This analysis found a net annual electricity bonus of 35 percent and a net summer peak electricity demand bonus of 52 percent.

Cooling coil discharge temperatures may need to be raised after a lighting retrofit to maintain comfort and ensure that electric reheat systems don't negate the lighting savings.



Source: Platts

There are several reasons why the summer peak benefits often will be greater than the cooling energy bonus. Because one doesn't heat in midsummer, no lost contribution to useful space heating needs to be subtracted from the peak cooling bonus (except with some reheat systems—see Figure 3-2). If daylight dimming is part of the lighting system, some of the lights won't be on much in the morning and early afternoon, thus reducing heat buildup in the hours leading up to the afternoon peak. In systems equipped with variable-speed drives, delivering less cooling means slower operation of pumps and fans, whose power consumption depends roughly on the cube of the flow they must deliver. Air conditioners are less efficient in the hottest weather, so using them less during peak periods saves proportionately more power than reducing their use at other times. Whether the peak demand reductions will lead to corresponding reductions in the demand charges on the electricity bill depends on whether the reduction occurs consistently throughout the period upon which the demand charges are based. While the net impact on HVAC energy and summer peak cooling demand may or may not be significant in a given building, moreefficient lighting will always reduce the amount of cooling capacity needed to cool the building. Because cooling capacity is very expensive ($3,000 or more per ton installed), lighting retrofits can virtually pay for themselves by stretching the capacity of the existing cooling system. This ounterbalances capacity reductions that can accompany conversion to non-chlorofluorocarbon refrigerants, so either there's no need to expand cooling capacity to serve new loads or a new cooling system can be made smaller than it otherwise would be (see sidebar for a sample calculation). In buildings with electric resistance heating, improved lighting efficiency will only switch the job of heating from one electric heater— the lights—to another—the electric resistance coils. However, if a building is heated by an electric heat pump, the heating system will have a better efficiency than the lights, or if a building is heated by natural gas, the cost of heating with the main system may be far less than the cost of heating with the lights. In the worst-case scenario, a building's heating system cannot satisfy the load without the aid of the heat provided by lights. While this scenario is unusual, improving lighting efficiency in this case would result in the need to increase the heating system capacity. Many HVAC systems deliver cold air throughout the building and use reheat coils or heating ducts to warm air back up to comfort conditions in particular spaces. Care should be taken to adjust reheat coils or increase the supply air temperature after lighting retrofits to maintain comfort and avoid energy waste. This should be part of the checklist for any lighting retrofit. Otherwise, people who were previously comfortable in summer might be uncomfortably cold after the lighting retrofit. Consider the constant-volume system with electric reheat shown in Figure 3-2—an inefficient but not uncommon type of airconditioning system. If you don't increase the supply air temperature after a lighting retrofit, the reheat coil will have to use more energy to make up for the reduced internal load. In this situation, there is no HVAC cooling bonus, and some of the electricity saved from the lighting retrofit is actually negated. To avoid this problem, reset the supply air temperature to a warmer temperature or, better yet, combine the lighting retrofit with a switch to a variable-air-volume air-conditioning system that avoids simultaneous heating and cooling.



Harvested Cooling Capacity

Saving 1 kW of lighting removes up to 3,412 Btu per hour (h) of heat. With 1 ton of cooling capacity equal to 12,000 Btu/h, each kilowatt of lighting saved reduces the cooling load by

$$\frac{1\text{ kW x } 3{,}412\text{ Btu/h/kW}}{12{,}000\text{ Btu/h}} = 0.28\text{ tons}$$

Assume that a lighting retrofit costing \$2/ft^2 reduces lighting demand from 3 watts/ft^2 to 1.2 watts/ft^2. This yields 1.8 kW of lighting savings per 1,000 ft^2 of upgraded space. That in turn equals a 0.5-ton (t) reduction in required cooling capacity:

$$1.8\text{ kW X } 0.28\text{ t/kW} = 0.5\text{ t}$$

Assuming that new cooling capacity and its associated ducts, electric service, drainage, and so on cost at least \$3,000 per ton installed, the lighting retrofit virtually pays for itself in freed-up or foregone expansion of cooling capacity:

$$\$3{,}000\text{/t X } 0.5\text{ t/}1{,}000\text{ ft}^2 = \$1.50\text{/ft}^2$$

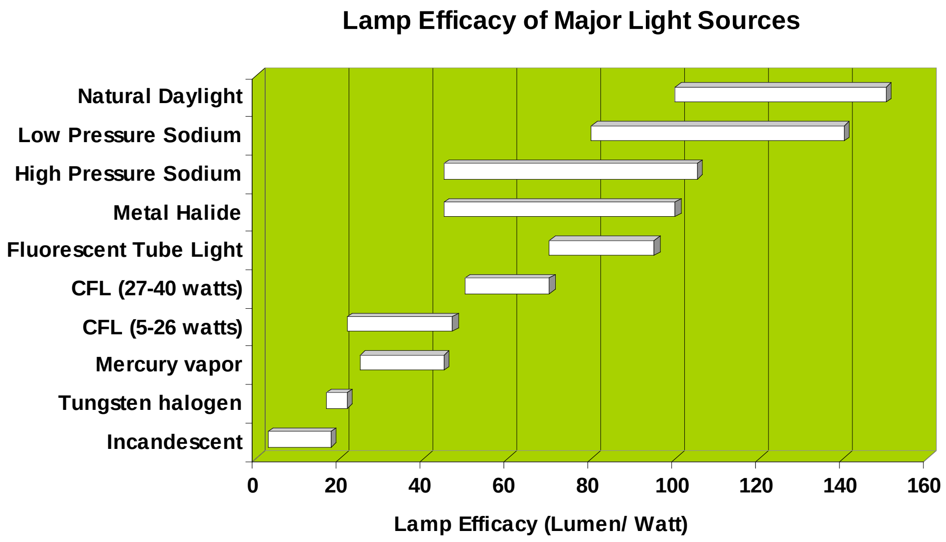
This is nearly as much as the total cost of the lighting upgrade.

4.2 Quantifying HVAC/lighting interactions

Researchers have made various attempts to quantify the interactions between HVAC systems and internal gain reduction resulting from lighting and other efficiency improvements. The HVAC system effects make it difficult to develop a single simplified method that will quantify the interactions for all building types. Detailed building simulation, which can account for system effects including potential cube-law fan and pump energy savings, is the best method for predicting the HVAC/lighting interaction in a given building. We present some of the results of research to date. In one study, weather data from 17 major cities was used to simulate the energy consumption of a 46,000-square-foot, two-story office building in different climates using different internal gains. The building used a closed-loop water-source heat pump system, divided into 16 zones with two heat pumps in each zone, and employed a 40,000-gallon storage tank to minimize the need for supplementary heating or cooling.

4.3 CONCEPT OF LUMINOUS EFFICACY

No lamp converts all the electricity it receives into light. Much of it gets turned into heat. The number of lumens that a lamp and its ballast (if there is one) produce per watt of power is called "luminous efficacy." For example, a 100-watt incandescent lamp that supplies 1,800 lm has an efficacy of 1,800 lm/100 watts, which is equal to 18 lm per watt. Be sure to consider whether ballast losses are included in an efficacy value; they can often add 20 percent or more to total power consumption. Typical efficacy ranges for the major types of light sources are shown in Figure below.



Lamp efficacy values are based exclusively on the lamp's performance and do not include ballast losses. System efficacy values measure the performance of particular lamp and ballast combinations and include the ballast losses. Why the term efficacy instead of efficiency? Because efficiency is a measure of some quantity, such as power, at the output of a device, divided by that same quantity at the input to a device. Efficiency does not have units.

Efficacy, on the other hand, is a measure of the output of a lamp in lumens, divided by the power drawn by the lamp or ballast in watts. Its units are lumens per watt. However, a lot more than the efficacy of the lamp and ballast determines the efficiency with which electricity gets turned into useful, high-quality light on the task. *The most efficacious light source is worthless if it is enclosed in a poor fixture that traps much of the light or reflects it at angles that cause eyestraining glare. Moreover, high-efficacy lamps can produce poor-quality light. High- and low-pressure sodium lamps have the highest efficacies available, but the light they produce generally has poor color and color rendering.*

Finally, manufacturer-rated lumen output is measured with a defined lamp orientation and temperature, but real-world conditions may differ widely from the laboratory, leading to different—generally less—light output than product ratings may suggest. ***Compact fluorescent lamps (CFLs), for example, are traditionally rated at 25° Celsius (77° F) in a base-up orientation. The efficacy of some CFLs can be 20 percent less in field applications where they are subjected to hotter conditions in a sealed fixture and mounted in a base-down position.***

4.4 LAMPS

4.4.1 INCANDESCENT LAMP TECHNOLOGY

An incandescent lamp consists of a tungsten wire filament enclosed in a sealed glass bulb. Voltage applied to the filament heats it to a high temperature, causing it to glow and produce visible light. Unfortunately, 90 to 95 percent of the power consumed by the hot filament is emitted as infrared (heat) radiation. Although inefficient from an energy standpoint, the luminous filament can be made quite small, thus offering excellent opportunities for beam control in a very small package.

Incandescent Improvements

Incandescent lamp efficacy ranges from under 10 to over 35 lm/W, depending primarily on filament temperature. Photometric efficiency (the efficiency of directing light produced by a lamp) also varies widely where reflective surfaces and shapes are involved. Several developments have improved the incandescent lamp, including the following:

- High-pressure halogen fill gas
- Longer-lasting filaments
- Different mixtures of fill gases
- Reshaping and coating of bulbs to focus light output
- Selective coatings to reuse waste heat
- Powering lamps at lower voltages

For over 50 years, incandescent lamps have been challenged by higher-efficacy light sources with lower life-cycle costs. For some applications, however, incandescent lamps are still the best choice. They have a low initial cost, provide easy dimming, and come in a wider array of sizes, shapes, wattages, and distribution patterns than any other light source. Refinements in incandescent technology continue to boost its performance, allowing for its selective use in energy-efficient designs.

- For the best performance, incandescent lamps must be matched to the fixture they are used with. For example, many recessed fixtures are designed for use with only reflector (R) or parabolic-aluminum-reflector (PAR) incandescent lamps. If standard (A-line) incandescent lamps are installed in these fixtures, much of the light generated by the lamp will be trapped inside the fixture.
- Although better incandescent lamps can provide slight energy-efficiency gains, the biggest savings come from replacing them with more-efficient fluorescent or high-intensity discharge (HID) sources. Improving incandescent fixtures without changing sources provides only marginal savings.
- When switching to more-efficient incandescent lamps or screw-in incandescent replacements, it is critical to avoid “snapback” to low-efficiency sources. Because standard Edison sockets can accommodate just about any screw-in lamp—from the most efficient halogen infrared floodlight to the least-efficient A-lamp—savings from an efficiency upgrade can be easily lost when the lamp is replaced.
- Utility incentives for high-efficacy incandescent lamps are rare. The most effective stance a utility can take on these lamps is to be aware of the best models available for the few applications that demand them and to allow their restrained use to enhance lighting aesthetics while maintaining an efficient overall lighting design.

4.4.2 FULL-SIZE FLUORESCENT LIGHTING

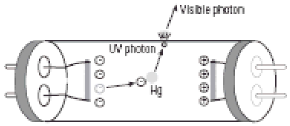
Fluorescent lighting dominates the commercial sector, which makes an examination of this technology’s efficiency—and the potential for improvements—particularly compelling. The installation of improved fluorescent lamps, ballasts, fixtures, and controls has been the bread and butter of both utility- and enduser-based energy-efficiency programs for several years. Exciting developments continue to mount in this important category of lighting equipment.

Fluorescent Lamps

The basic fluorescent lamp contains lowpressure mercury vapor and inert gases in a partially evacuated glass tube (See Figure 7-2).

Figure 7-2: Fluorescent lamp operation

Fluorescent lamps maintain an electric arc through gas, in contrast to the continuous metal filaments used in incandescent lamps.

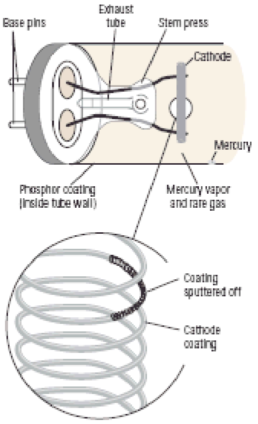


Notes: Hg = mercury; UV = ultraviolet

Source: Platts; adapted from *IESNA Lighting Handbook* [2]

Figure 7-3: Fluorescent lamp electrode construction

Electrode erosion eventually causes lamp failure.



Source: Platts; adapted from *IESNA Lighting Handbook* [2]

The mercury atoms are energized by collisions with free electrons that have been excited by an electric field. As they descend back to the lower energy state, the mercury atoms emit ultraviolet (UV) photons that then strike phosphors—specially formulated compounds that line the tube. Another round of excitation and de-excitation causes the phosphors to emit visible photons, or to fluoresce. Altering the phosphors produces different qualities of white light. All fluorescent lamps use a power-conditioning device called a ballast. Although ballasts perform various functions, their primary role is to control the operating current of a fluorescent lamp or other type of discharge lamp. Ballasts also typically provide the high voltage necessary to start the lamp, provide power to heat the electrodes in many types of fluorescent lamps, and ensure control and safety in a variety of failure modes. Ballasts and starting methods are discussed in Section 7.2. Ballast-conditioned power is supplied through contacts in metallic or plastic end caps (called bases), which feed electrodes at each end of the lamp. The electrodes are formed from coiled tungsten wire coated with an electron-emissive material such as barium oxide. When heated, this material releases electrons into the tube to create and maintain the arc. The primary reason for fluorescent lamp failure is the depletion of barium from the electron-emissive material or the erosion of this material on the electrodes (Figure 7-3).2 This depletion or erosion, which occurs more rapidly during lamp ignition, also deposits cathode material onto the lamp walls, creating the familiar lamp-end blackening.

Lamp bases contain contacts designed to control their compatibility with different starting methods and power loadings. In general, a design with two pins or recessed contacts on each end implies rapid start or preheat start, whereas a single electrical contact indicates instant start. There is an important exception: All manufacturers offer T8 lamps with bipin bases that can be rapid-started or instantstarted. For operation with instant-start ballasts, the socket contacts at each end of these lamps must be wired together within 4 inches (in.) of the lamp holder to act as one.3 Fluorescent lamps differ primarily in their size, type of phosphor coating, fill gas, and base/cathode design. By varying these four characteristics, manufacturers create lamps that span a wide range of wattages, light outputs, colors, and lifetimes. Diameters range from 0.250 to 2.125 in. and lengths from 6 to 96 in. Nominal power consumption (without ballasts) ranges from under 20 watts to over 200 watts, and light output also spans an order of magnitude: from under 1,500 lumens (lm) to over 15,000 lm. Lamp-only efficacy covers a smaller range: from 60 to 100 lumens per watt (lm/W). As shown in Figure 7-4, lamps are designated primarily by their wattage or length and tube diameter.

4.4.3 COMPACT FLUORESCENT LAMP TECHNOLOGIES

Compact fluorescent lighting is a key tool for achieving energy efficiency in many common applications formerly dominated by incandescent lamps. Although compact fluorescent technology can provide energy savings of up to 75 percent and slash maintenance costs, the real challenge is to obtain excellent visual quality with these compact sources. The experience of lighting designers, lamp and fixture manufacturers, and system users provides valuable guidance on how to apply—and how not to apply—compact fluorescent lamps. These lessons are especially salient as federal programs like Energy Star expand the use of compact fluorescent technology in the commercial and residential sectors.

- During the past five to six years there has been a virtual explosion of new CFL products and vendors. CFLs from the major manufacturers are now available with power ratings that range from 5 to 34 watts for self-ballasted versions and with ratings of up to 120 watts for pin-base lamps designed for use with dedicated ballasts.

- Self-ballasted CFLs have decreased in size so that many are now as small as the incandescent lamps they are designed to replace, which means they will fit into a greater variety of incandescent lamp fixtures.
- Electronic ballasts have replaced magnetic ballasts in virtually all self-ballasted CFLs.
- In addition to the original multi-tube designs, CFLs are now available in spiral configurations that are optically more efficient and considered by many users to be more attractive.
- Self-ballasted CFLs are available with permanent or removable reflectors or A-line-, globe-, or cylinder-shaped translucent covers.
- At least one lamp company produces selfballasted CFLs with power ratings as high as 105 watts. Self-ballasted CFLs rated for greater than 34 watts should be used with caution, especially in base-up, recessed, or enclosed fixtures. In these applications, lamp heat that cannot easily escape will rise convection and overheat the ballast, potentially leading to short ballast life.
- Dimmable self-ballasted CFLs that operate on phase control dimmers for standard incandescent lamps have become available in recent years, as have other models that operate in standard three-way incandescent sockets. Many dimmable ballasts are also available for dedicated CFL systems, but costs remain higher than desirable.
- Self-ballasted CFLs are available for less than $5.00 each.
- Early claims about light output, energy savings, and lifetime for CFLs were sometimes exaggerated because these assertions did not fully include the effects of ambient temperature, cycling, mounting position, fixture performance, and lumen depreciation. The introduction of mercury amalgams has addressed the mounting-position issue and partially addressed issues related to ambient temperature. The remaining concerns are not unique to CFLs and should be taken into account in any design that uses either linear or compact fluorescent lamps.
- Fixtures equipped with high-efficacy CFLs are now available in just about every design that is typically used with incandescent lamps. Most of these fixtures are available with high- performance electronic ballasts.
- One of the most important yet underrated benefits of CFL technology is the dramatic reduction in relamping-associated labor costs it offers compared with incandescent lamps.
- Lighting manufacturers have responded to utility concerns about poor power quality by developing specific self-ballasted CFLs with high power factors and low harmonic distortion. High power factors are the norm for pinbase CFLs with dedicated electronic ballasts.

“Energy-saving” lamps

In the 1970s, lamp manufacturers found that adding krypton gas to the standard argon gas fill reduced both energy consumption and light output when used on ballasts designed for “standard” lamps. This allowed facility managers to reduce lighting energy consumption without delamping or dealing with the expense of replacing ballasts or luminaires. Thus was born the “energy-saving” (ES) lamp—but the term can be misleading, because these lamps have about the same efficacy as the higherwattage lamps they are designed to replace.

For new installations it is almost always better to consider new, high-efficacy systems—such as electronically ballasted T8 lamps with the appropriate ballast factor for the application— than to save energy by using a

T12 ES lamp with an older, high-wattage ballast. A recent development is the T8 ES lamp that can be used to reduce energy consumption in systems designed for conventional T8 lamps. These ES lamps are available in 28-watt and 30-watt versions as compared with the standard 32-watt T8. Most ES lamps are T12s, however. Brand names for this lamp category are listed in Table 7-3. The primary attraction of ES lamps is, as stated above, that they offer a simple energy-saving relamping option for the multitude of existing T12 applications, especially those that are overlit. Some facility managers prefer ES "retrofits" because no ballast change is required, so the need for any real electrical work is eliminated. Unfortunately, both T8 and T12 ES lamps have some operational shortcomings. They are very sensitive to lower-than- rated operating current and therefore cannot be deeply dimmed or run on low-ballast-factor ballasts. ES lamps also perform poorly in cold temperatures and should not be placed in the air draft from air-conditioning systems. Perhaps the greatest drawback to T12 ES lamps is that their use may either impede the path to future upgrades (such as T8 conversions) or convey the impression that because "energy-saving" lamps are in place, maximum efficiency has been achieved. When weighing the pros and cons of ES lamps over other options, compare their rated "mean lumens" and "initial lumens" to assess their long-term performance, and remember that lower light output accompanies the wattage reduction that ES lamps provide.

Premium lamps

Some manufacturers offer a range of premium-grade fluorescent lamps that provide compliance with mercury disposal regulations as well as improved color rendering, lumen maintenance, efficacy, and lifetime. These lamps employ special coatings between the glass and the phosphor; more expensive, high-performance rare earth phosphors; more rugged electrodes; or a combination of all three. Premium fluorescent lamps are available in a range of lamp types, but they are most common in the popular universal-/rapid-/ instant-start T8 lamp family. Premium fluorescent lamps may cost two to three times as much as standardperformance lamps.

The best of the premium lamps have been unofficially dubbed "super-T8" lamps. These lamps, combined with super-T8 ballasts, represent enough of an improvement over earlier generations of T8 lamps that they can be used to cost-effectively retrofit facilities where old T12 systems have been replaced with what is already old T8 technology. A handful of energy service providers (ESPs) have started to provide incentives for this super-T8 technology (see sidebar).[5] Typical requirements include initial output of at least 3,100 lm, a CRI of at least 81, and a mean efficacy of at least 90 lm/W.

4.4.4 HIGH-INTENSITY DISCHARGE LIGHTING

High-intensity discharge (HID) lighting sources are the primary alternative to high-wattage incandescent lamps wherever an intense, concentrated source of light is required. Although HID lamps can provide high efficacy in a wide range of sizes, they have special requirements for start-up time, restrike time, safety, and mounting position. Replacing incandescent fixtures with HID lighting requires careful consideration of these issues as well as the lumen depreciation and color-shifting characteristics that many HID sources exhibit.

Highlights

- HID lamps can provide very high efficacy, offering energy savings of 50 to 90 percent when replacing existing incandescent sources. Efficiency upgrades within the HID family can provide smaller but significant savings of about 10 to 50 percent.
- Mercury-vapor lamps are becoming virtually obsolete as other HID sources with better efficacy, color rendering, and lumen maintenance have become available at lower cost, especially in larger lamp sizes. At the smaller end of the spectrum, MV lamps can be replaced in most applications with screw-in compact fluorescent lamps.
- A new type of MH lamp introduced in recent years is based on ceramic arc tubes—such as those used for HPS lamps—rather than quartz arc tubes. These ceramic metalhalide (CMH) lamps are

more expensive than quartzbased MH lamps and currently have lower rated lifetimes, but their color rendering, color uniformity, and efficacy are higher. This allows them to be used in some color-critical applications that previously required incandescent lamps.

- Pulse-start metal-halide lamps have a single electrode at each end of the arc tube, rather than the second "starting" electrode at one end of the arc tube that most conventional MH lamps have. Pulse-start MH lamps offer improved lumen maintenance, increased efficacy, longer life, and quicker hot-restrike than conventional MH lamps. But they require a high-voltage starter and a high-voltage, "pulse-start-rated" socket.
- Small HID fixtures are appearing as the metal-halide and HPS families expand to include smaller reflector lamps, more lamps that can be safely used in open fixtures, and lower-wattage single-ended lamps.
- Special CMH lamps have been developed for operation on HPS ballasts. These lamps provide a white light that is typical of other MH lamps, and they can be directly retrofitted into HPS fixtures.
- Electronic ballasts for HID lamps are becoming available from a number of vendors. But unlike electronic ballasts for fluorescent lamps, HID lamps' energy performance is not greatly improved with these ballasts. The primary benefits of electronic ballasts for HID lamps are reduced size, weight, and noise as well as better control of color and lumen maintenance.

4.4.5 OTHER LIGHTING SOURCES (LEDS)

In addition to the conventional illumination sources described in the preceding chapters, a variety of other lighting technologies are available or in development—some with high energy efficiencies. Each source type has unique operating characteristics, advantages, and limitations. Most of these technologies are best suited for special applications rather than for general area lighting. High-brightness "white" light-emitting diodes and "white" organic light-emitting diodes are two emerging technologies that deserve close attention during the next 5 to 10 years.

- Light-emitting diodes (LEDs) are increasing in efficacy, light output, and color availability while dropping in cost. Highbrightness narrow-band or various-color LEDs are being used increasingly in vehicle signal lights, traffic signal lights, exit signs, and decorative and information display applications. Composite units of red, green, and blue LEDs, or of systems composed of a blue or violet LED plus a phosphor coating, are being used to create white light with an efficacy equal to that of conventional incandescent lamps, further expanding LED applications.
- If their lifetime can be increased and if production problems can be smoothed out, electroluminescent products may be suitable for signage and other applications not well handled by other sources.
- Organic light-emitting diodes (OLEDs) generate light using physical processes similar to those used by LEDs, but they are more similar to electroluminescent light sources in application and manufacture. Long-life, high-efficiency OLEDs will displace electroluminescent light sources in many applications, and they could displace even fluorescent sources in some applications if current research and development programs lead to significant increases in life and efficacy.
- Recent improvements in photoluminescent products ("glow-in-the-dark" materials) give them the potential to replace powered lighting in select applications.

- Radioluminescent materials that glow from nuclear decay require no electrical power, but their application is severely limited because of significant safety concerns. Most firms producing tritium units (primarily for exit signs) have diversified into LED products and are phasing out signs containing tritium.
- High-frequency, induction-coupled fluorescent lamps are a viable option for area and specialty lighting, but their efficacy is currently not as good as that of the best conventional fluorescent systems. The main advantages of high-frequency, inductioncoupled fluorescent lighting are the ability to produce a substantial amount of light in a relatively compact package and long lamp life due to the elimination of the electrodes.
- Sulfur lamps, driven by microwave energy, are a potentially valuable light source, especially if combined with advanced lighting distribution technologies, such as fiber optics. While the only sulfur lamp manufacturer and owner of sulfur lamp technology, Fusion Lighting, is no longer producing or designing sulfur lamps, the possibility exists, as of early 2004, that Fusion Lighting might sell its sulfur lamp patents to another company that would continue development of this interesting product.

4.5 FIXTURE & REFLECTOR

Architectural elements in the space may also present opportunities to adjust luminance ratios, particularly by hiding lamps so they cannot create large differences in luminance between fixtures and their surroundings. Basic measures for improving lighting quality include the following:

- Choose fixtures that recess and/or cover the lamp and distribute its light by reflection, refraction, or diffusion.
- Place the light source behind or inside a cornice, cove, valance, or trough.
- Use indirect fixtures and bounce the light off the wall and/or ceiling.
- Use lamps or fixtures with narrow beam spreads to highlight small areas.
- Raise the light source or recess it into the ceiling.
- Add dimming controls to allow for reductions in fixture light output.

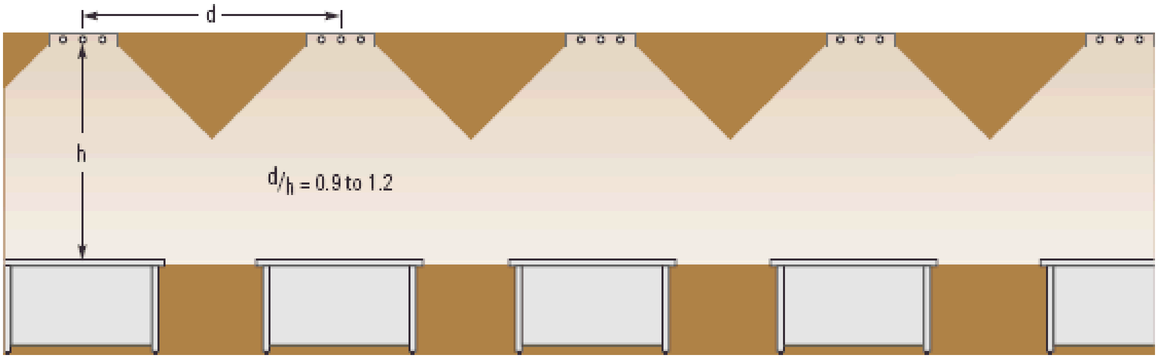
General rules for spacing fixtures help avoid major foot-candle variations within a space. Do not, for example, place a ceiling fixture closer than 1 foot (ft) from a wall; doing so creates a “hot spot” on the wall. Unless there is a logical reason to vary lighting levels (such as merchandising), avoid variances at task heights directly below and between fixtures by observing the proper spacing methods.

4.5.1 DETERMINING FIXTURE SPACING

There are two methods to calculate fixture spacing:

- *Spacing-to-mounting-height (S/MH) ratio* is applied parallel to the lamp’s (and usually fixture’s) length and perpendicular to the lamp’s length to assure an even foot-candle level between and below the fixtures, which is preferably less than a 20 percent variation.

The recommended spacing-to-mounting-height ratio of most 2-by-4-foot fluorescent fixtures is between 0.9 and 1.2. That means the center-to-center distance (d) measured across the fixtures should be 0.9 to 1.2 times the distance between the bottom of the fixture and the height of the desk or other task surface (h).



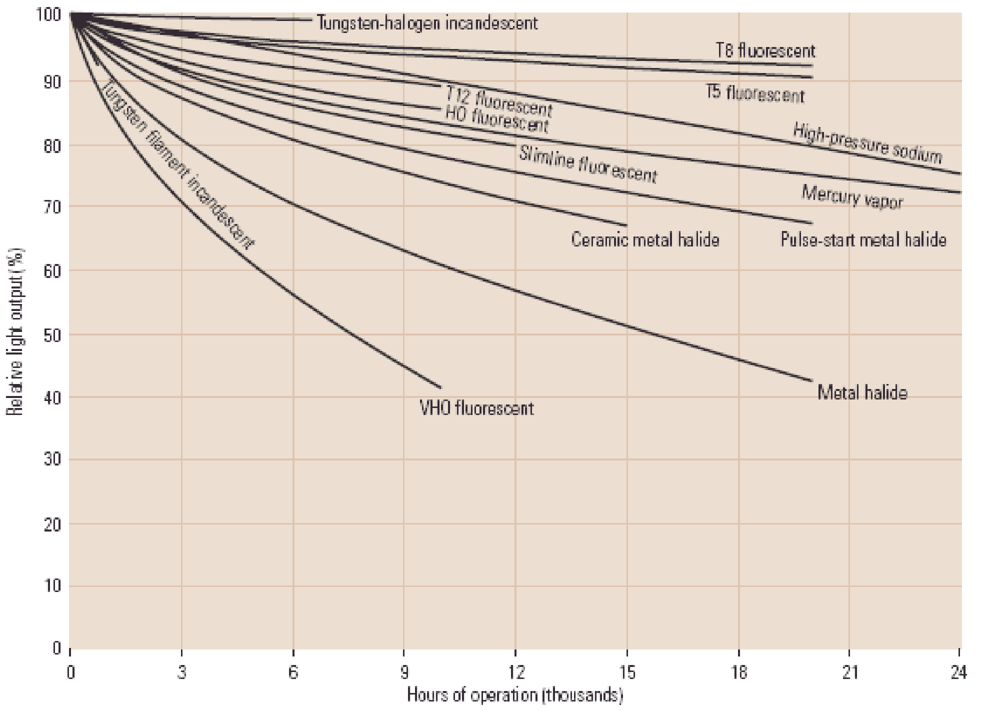
Source: Platts

Typical 2-by-4-ft fixtures have S/MH ratios of 0.9 to 1.2 going across them, meaning that the center-to-center spacing of the fixtures should not be more than 1.2 times farther apart than their height above the task (See Figure 2-1). A similar number exists for spacing end to end. These ratios are the most common method to check maximum fixture spacing. Manufacturers list the recommended S/MH ratios for their fixtures. For retrofits where the placement of fixtures is already determined, users can ask reflector manufacturers for reflector kits with the appropriate S/MH ratio for the space.

- *Spacing criterion (SC)* is a single number that indicates the diagonal spacing needed to assure that light at the cross point of diagonals connecting the centers of four fixtures will be the same as light levels directly below the fixture. SC and S/MH are often numerically close for typical fixtures. These ratios are actually fairly conservative because they assume no surface interreflectances (for example, off walls), which tend to soften variations. Some variation in levels between fixtures is allowable since the eye generally doesn't notice variations under 50 percent (that is, from 40 to 60 foot-candles). Special reflectors and lenses are available that can spread light farther, thus mitigating the need to add fixtures between those found to be installed farther apart than justified by their catalog-value spacing ratio. Such devices usually add cost to a retrofit but greatly improve light-level consistency.

4.6 OPERATION AND MAINTENANCE ISSUES

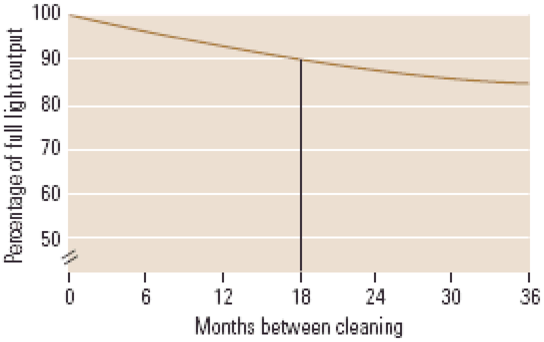
The light output of lamps declines over time.



Notes: HO = high output; VHO = very high output.

Source: Platts; data from National Lighting Bureau [5]

Even in clean office environments, 18 months of dirt buildup can reduce light output by 10 percent.



Source: Platts

5 TECHNOLOGY TIPS

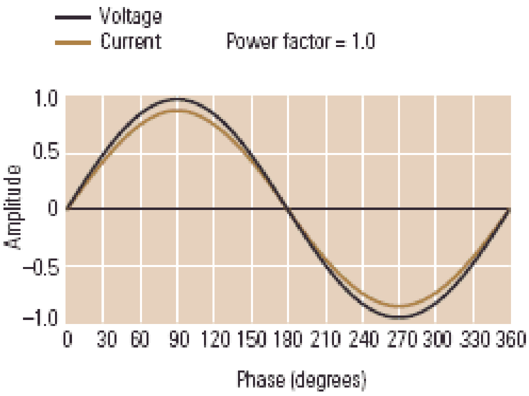
5.1 POWER-QUALITY EFFECTS

Lighting systems can influence and be influenced by the power factor and harmonics characteristics of the electrical environment in the building.

5.1.1 POWER FACTOR

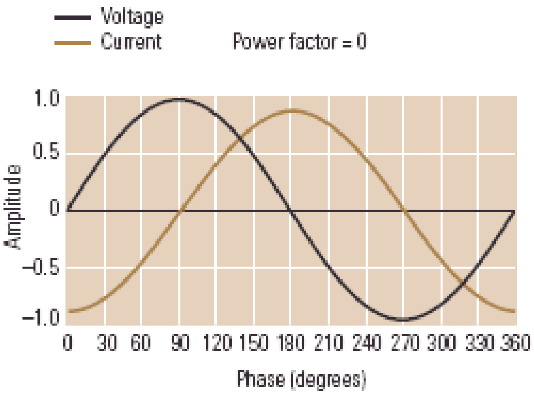
Power factor, which is defined as the ratio of watts to volt-amperes (also expressed as the ratio of real power to apparent power), is an indicator of how much of a power system's capacity is available for productive work, so it is an important and constant concern for utilities and large power users alike. Purely reactive loads will have phase angles of 90 degrees (as shown in Figure 3-1 and 3-2) and will carry phase power factors of zero. It is only correct to use the phase power factor approach to measure power factor when there is no significant waveform distortion.

The graph shows in-phase voltage and current waveforms.



Source: Platts

Voltage and current waveform are 90 degrees out of phase in this inductive load.



Source: Platts

The power factor reflects how much of the power drawn by the load is real and thus able to do work. It is the ratio of the actual power being used in a circuit to the power that is apparently being drawn from the supply line. The lower the power factor, the greater the apparent power for a given amount of actual power. This excess of apparent power cannot do work at the load but requires sufficient capacity to carry it throughout the grid and the local distribution system, and it incurs its share of system losses. Though excess apparent power cannot do real work, it has real and large costs.

5.1.2 HARMONICS

Harmonics are voltage and current frequencies (in integral multiples of the fundamental frequency) riding on top of the normal voltage and current waveforms. Current harmonics are induced onto the power line by nonlinear electronic equipment and systems (including lighting ballasts). Voltage distortion typically results from current distortion reacting with system impedance. These harmonics usually lumped together as total harmonic distortion (THD), perform no useful work and can be a significant nuisance.

Many utility demand-side management (DSM) programs limit their incentives to lighting products with high power factor (>0.9) and low harmonic distortion (<0.32) — and with good reason. Products with low power factor and high levels of harmonics can cause problems in the utility and customer facilities. Low-power-factor equipment requires more current to perform the same work and can overload wiring or cause greater resistive losses in wires. More transformer capacity gets used, eliminating its availability for new equipment or higher system loads. In extreme cases, overall system voltage may drop, affecting the operation of other equipment supplied by the same transformer. And if the utility has a separate charge for low power factor, the customer's bill will be higher. High harmonics can cause interference with other sensitive equipment and may induce hazardous currents in the neutral wiring of the building, increasing the risk of fire and electrical shock.

A related problem can occur when you partially alter a lighting system. Lighting uses single-phase power, so a building's lighting load is typically divided equally among all three phases of an electric service. If the lighting load is reduced on one phase but not the others, the current in the neutral line may increase, creating a hazard and greater line losses. As an example of what can go wrong by ignoring these issues, consider the impact of a lighting retrofit that raises light levels by replacing incandescent lamps, having a power factor of 1.0, with compact fluorescent or high-intensity discharge (HID) lighting that as a low power factor of 0.35. The base case is a dimly lit lobby with twelve 100-W incandescent fixtures, each drawing about 0.8 amps for a total draw of 9.6 amps. One could double the light levels, while substantially decreasing kilowatt-hour use, by replacing the incandescent lamps with 50-W high-pressure sodium (HPS) lamps having magnetic ballasts, each of which dissipates 8 watts and has a power factor of 0.35. From an energy point of view, this seems like a good strategy. But each of the HPS lamps will draw 1.38 amps, so 12 of them will draw a total of 16.5 amps, resulting in a 7-amp (72 percent) increase in wire load, which may lead to overloaded circuit breakers and possibly burned-out wall switches. To avoid such situations, discuss pending renovations with a facility's electrical maintenance supervisor to be sure loads can be balanced once the job is done. Use lowharmonic (<0.32) and high-power-factor (>0.90) electronic ballasts. Note that socalled normal-power-factor magnetic ballasts typically have power factors of 0.4 to 0.6 while high-power-factor magnetic ballasts have power factors of 0.9 or greater. Many electronic ballasts have power factors of 0.95 or higher. Be particularly aware of these issues when replacing incandescent lamps, which have a power factor of 1.0. In these cases one should consider using fixtures or retrofit devices, which have built-in powerfactor correction capacitors for magnetic ballasts, or high-quality electronic ballasts instead of magnetic ballasts. Increased concerns from utilities and users sensitive to power quality are creating a stronger market for equipment with "clean" power-quality characteristics. The European Community (EC) adopted a regulation requiring all electronic equipment over 50 W sold in the EC to carry power-factor correction components.

5.2 BALLASTS AND POWER SUPPLIES

The primary functions of ballast are to provide cathode heating where necessary, initiate the lamp arc with high-voltage, provide lamp operating power, and then stabilize the arc by limiting the electrical current to the lamp. Secondary functions include input power-quality correction and control features such as lamp dimming or compensation for lumen depreciation. Substantial discounts for the purchase of the large number of ballasts needed for new construction or renovation can be obtained from manufacturers through bulk procurement policy. Ballasts last for 40,000 to 100,000 hours and operate with an electrical efficiency of about 80 to 95 percent, consuming parasitic power of about one to a dozen or so watts. As the central connection point for fluorescent lighting systems, ballasts are the key to achieving synergistic energy savings by controlling light output. Ultimately, the most promising avenue for this control is the lowcost dimmable fluorescent ballast, which allows users to take advantage of strategies such as automatic daylight dimming, lumen depreciation compensation, occupancy controlled and scheduled dimming, and manual task dimming. Currently available dimming fluorescent ballasts and controls do not yet make these features available at low cost. Observers vary in their optimism about the development of a reliable, inexpensive (say, under Rs. 600 for a two-lamp F32T8 unit) dimming fluorescent ballast. Some say it will never happen, but others claim that welldesigned "energy-dimming" ballasts can be built to sell for little or no more than nondimming products. Most dimming ballasts are high-cost units designed for use in conference rooms and other locations where dimming to a very low level is required. The arrival of inexpensive dimming equipment designed for the moderate level of dimming required for use with daylight and peak-load-shedding controls will dramatically increase the potential energy savings in fluorescent lighting systems. The availability of low-cost dimmable CFLs, shows that it is technically feasible to design and manufacture dimming ballasts for linear fluorescent lamps that are only marginally more expensive than nondimming electronic ballasts. Most ballasts in service today are magnetic units that consist of little more than an integrated transformer and inductor, a capacitor, and a thermal cutoff switch to protect the ballast from overheating. Hybrid ballasts use electronic circuitry to control power to the lamp's cathodes, but magnetic components still drive the main arc. In high-frequency electronic ballasts, the size and weight of the magnetic devices required for current and voltage control are greatly reduced. Additional small magnetic devices are used for surge/spike suppression and other protective functions.

5.3 LIGHTING DESIGN TOOLS

5.3.1 SOFTWARE FOR ENERGY-EFFICIENT LIGHTING

Lighting software helps users compare lighting alternatives and make sure that the ultimate design choice will provide quality light. Demands on lighting designs are becoming more complex as both lighting quality and energy efficiency have become high priorities. In addition, a wide range of variables—different light sources, fixtures of varying efficiency and photometrics, and rooms with a wide range of geometries and surface finishes—all make lighting design a challenge worthy of computer modeling. In particular, the trend among fixture manufacturers to use specular reflectors that send light in particular directions makes modeling more useful than it was with the old-style, white-painted diffuse reflectors. Most computer models can also simulate the effects of daylight and can be used to help designers develop effective control strategies for getting the optimum blend of electric lighting and daylighting. Once constructed, a computer lighting model can be easily modified so that various fixture designs and spacings can be evaluated and compared in terms of horizontal and vertical light levels. Designs that give the proper quality and quantity of lighting can then be evaluated for their energy consumption, and the design that gives both the desired lighting quality and the lowest life-cycle cost can be selected. Output from lighting software can also be input into software that models an entire building to enable analysis of the impacts of lighting decisions on other building systems. Lighting professionals who do not first model the design face the risk of getting poor light distribution or more light then they expect. Both problems can be difficult and expensive to correct. Computer software for developing a lighting model can be costly to buy and requires expertise to use, but companies can obtain the models as a service—often from a lighting fixture manufacturer or lighting design firm. These companies have trained personnel who know how to make the right assumptions and develop an accurate model after only an hour or two of work. As with any computer model, making the correct assumptions is crucial to obtaining an accurate and reliable result. Using the correct values of reflectance for the various surfaces to be found in a room is particularly important—and it is difficult for the untrained user. Different finishes on walls and ceilings, floor coverings, furnishings, and windows all influence the values of reflectance that should be used to give the best results. The most widely used are Lumen Designer (formerly called Lumen Micro) and AG132. These and other comprehensive modeling packages available today include capabilities for determining expected light levels and distribution. The models also feature glare-rating calculations; lighting power density computation; and rendering capabilities that provide realistic views of what an illuminated space will look like. Daylighting calculations are also becoming increasingly important, and both leading packages now offer that capability. In order to be useful, the most sophisticated software tools require training and experience on the part of the user, but numerous simpler programs are also available for the designer who does not need all the functionality of the most complex products. A number of lighting software tools are also available free of charge. They come from government agencies and private companies, and they offer a wide range of capabilities. More information about lighting software is available from the Building Energy Software Tools Directory maintained on the U.S. Department of Energy Web site. In addition, The Illuminating Engineering Society of North America periodically conducts a survey of lighting software tools and publishes the results in its magazine *LD+A* (*Lighting Design and Application*). A number of software tools are available for assisting in the design of daylighting systems and for predicting the energy savings that will result from daylighting design strategies.

AGI32

AGI32 is a lighting design tool from Lighting Analysts Inc. that adds daylighting capabilities in Version 1.6. For more information, go to the Lighting Analysts Web site at www.lightinganalysts.com.

BEEM

BEEM is a simplified, menu-driven set of calculations that permits an economic evaluation of various lighting controls as well as the optimization of many fenestration parameters for side-lighting applications. BEEM is compatible with EPRI's LightCAD, an AutoCAD-based electric lighting evaluation tool. BEEM is available for $50 from R.A. Rundquist & Associates, tel 413-586-7743, or free to EPRI member utilities from the EPRI Lighting Information Office at tel 510-444-8707. BEEM is available only as an MS-DOS-based program. A Windows version has never been developed.

DAYSIM

Based on LBNL's Radiance software, DAYSIM is free software used to predict the availability of daylight and electric lighting energy demands in individual offices that use manually and automatically controlled lighting and blind systems. It makes use of daylight simulations combined with a user-behavior model based on field studies in office buildings. The software was developed by the Institute for Research in Construction of the National Research Council Canada. For more information, e-mail Christoph Reinhart at christoph.reinhart@nrc.gc.ca.

DESKTOP RADIANC

Desktop Radiance is a Windows 95/98/NT software package for lighting and daylighting simulations developed at LBNL. Desktop Radiance is designed to work with AutoCAD Release 14. It includes libraries of materials, glazings, luminaires, and furnishings so users can quickly create realistic lighting models. Desktop Radiance can be downloaded from the Desktop Radiance Web site. There is no charge for either commercial or noncommercial use, but there are restrictions on redistribution, reverse engineering, and resale. For more information, see http://radsite.lbl.gov/deskrad/dradHOME.html.

LUMEN MICRO 2000

Lumen Micro is a menu-driven program that calculates daylight and electric light levels. It is available for $695 from Lighting Technologies, Denver, Colorado, tel 720-891-0030, web www.lighting-technologies.com.

VIRTUAL LIGHTING SIMULATOR (VLS)

The developers of this new tool, at LBNL's Building Technologies Department, created a database by simulating a large number of cases with Radiance. Using VLS, an architect or engineer can see the effects of varying window sizes, building orientations, and glazings in seconds with the click of a mouse. VLS is available on the Web at http://gaia.lbl.gov/vls. The daylighting module currently only covers small office spaces and is only suitable for buildings located at the same latitudes as southern California (about 34° N). The current system was developed with funding from Southern California Edison through the California Institute for Energy Efficiency. LBNL developers are looking for funds to extend VLS' capabilities. For more information, contact Konstantinos Papamichael at LBNL, e-mail k_papamichael@lbl.gov.

6 LIGHTING CONTROL TIPS

6.1 DIMMING

It often makes sense—and saves dollars—to dim or turn off electric lights when natural light can provide good illumination. In the U.S., energy codes in some states require that automated dimming controls be installed in areas considered to be daylit. Many energy service providers also advise customers to use daylight dimming systems whenever they design for daylighting. For example, through its Daylighting Initiative Program, Pacific Gas and Electric Co. has developed a range of design tools and case studies to promote daylighting systems in which automated controls play a key role in achieving energy savings. However it is important to remember that with fluorescent lighting, currently available dimming ballasts are less efficient than the best non dimming ballasts. Analyses of the savings potential should take that difference into account.

So far, simple dimming systems that control a number of lights with a single sensor have proven to be quite successful in atria, hallways, spaces are likely to be preoccupied with other matters (so changing light levels tend to have little impact on them). However, there is strong evidence that sophisticated daylight dimming systems are not performing as well as designers had hoped when the controls are placed in environments where workers do feel "ownership" of their spaces. Due to poor design or errors in installation, some systems have failed to save enough electricity to offset costs for procurement, installation, and maintenance. In some cases, these systems have proven to be downright bothersome, leading workers to complain about glare, abrupt changes in lighting levels that interrupt "fixed" visual tasks (like staring at a computer screen), or low light levels—especially if they can't easily override automatic settings.

Disenchanted teachers in classrooms and company vice presidents in perimeter offices have been known to tape over daylighting sensors to raise light levels. And complaining to maintenance personnel about such lighting problems may result in the dimming system being completely disabled, especially if the maintenance team has not been trained in the subtleties of adjusting lighting system controls. Whenever this happens, the energy-saving benefits of daylighting are reduced to zero.

- *Stair-step switching*, in which lights can be adjusted at several levels or different banks of lights can be controlled separately.
- *Open-loop continuous dimming*, in which the photo sensor monitors incoming daylight but not the electric lights that are turned on in response to the daylight signal.
- *Closed-loop dimming*, in which the photo sensor monitors daylight and electric light, and its output is used to adjust the electric lights.

One of the conspicuous drawbacks of CFL technology has been the lack of cost-effective dimming options for pin-base lamps. The main reason for the lack of hardwired dimming ballasts for pin-base CFLs is not technical but economic. Any four-pin lamp can be dimmed as long as cathode voltage is maintained. High-quality hardwired dimming ballasts are available for pin-base CFL lamps ranging from a low of 13 watts to a high of at least 42 watts. The problem is that these dimming ballasts cost two to three times as much as equivalent nondimming ballasts. This high cost is created by a number of factors: low sales volume; high profit margins on what is perceived to be a niche product; and the fact that the ballasts are designed to dim to 1 or 5 percent of rated light output, which produces lower output than needed in many applications such as restaurants and hotels. There is no fundamental technical reason why a dimming ballast should cost even twice as much as a nondimming ballast. Most of the cost of an electronic ballast is in the power delivery components, not the control circuit. However, manufacturers seem unwilling to lower prices until sales volume increases, and customers will not start to purchase dimming ballasts in large quantities until prices come down. It is interesting to note that in Europe about 30 percent of fluorescent lamps are operated by dimming ballasts, whereas in the U.S. the number is closer to 3 percent.25 Dimming for screw-base products, including both self-ballasted and modular products, faces a more difficult technical challenge, because these lamps are intended to be operated in fixtures designed and wired for incandescent lamps. Some of these fixtures are connected to phase-control dimmers that were designed for incandescent lamps and are incompatible with conventional electronic or magnetic lamp ballasts. However, in the past few years Philips, GE, and TCP have started offering self-ballasted and modular CFLs with special electronic ballasts that can be dimmed using a conventional phase control incandescent dimmer.

These same companies also sell three-way CFLs designed to work in conventional threeway incandescent sockets. The dimmable selfballasted CFLs typically cost 1.5 to 2 times as much as equivalent nondimmable self-ballasted CFLs. However, payback times for threeway dimmable CFLs can be very attractive because of the high cost of three-way incandescent lamps. Continuously dimmable and three-way self-ballasted CFLs typically sell for less than $20, which is much less than the price of dimmable stand-alone ballasts for pin-base CFLs. One reason for their lower cost is that the self-ballasted products dim only to about 10 to 30 percent of full lighting output, whereas hardwired ballasts are typically designed to dim to 5 percent of full output or less. However, the large price difference between self-ballasted dimmable CFLs and dimmable stand-alone ballasts for CFLs is one indication that there is substantial opportunity for the price of stand-alone dimmable CFL ballasts to be reduced. There are various ways to achieve a dimming effect, including the following:

- Intelligent design with a mix of light sources, including some that don’t dim and others that do.
- Multiple lamps on separate controls.
- Step dimming.
- Continuous dimming.

Not all light sources in a space necessarily need to be dimmable in order for a dimming effect to be created. In settings such as conference rooms, on/off CFLs can be used for general ambient lighting and dimmable incandescent lamps can be used for low ambient light during presentations. This can often be much less expensive than using dimming CFL technology throughout, because the increase in energy use is only minimal when compared with an all- CFL approach. Another option is to wire CFL downlights in every-other-fixture patterns and place them on separate switches so that each switch controls alternating fixtures. Because many CFL fixtures yield wider and more even light distribution than most incandescent installations, this approach can work well as a “dimming” strategy without creating hot spots and dark zones. Three-way switching of CFLs is available for both floor and table lamps in two different ways. The first method uses the GE, Philips, or TCP three-way self-ballasted CFLs discussed above, which can be used in any threeway fixture. The second uses floor and table lamps (fixtures) with circline CFLs and dedicated three-way electronic ballasts.

6.2 OCCUPANCY CONTROLS

Occupancy sensors can be a cost-effective energy-saving tool if applied properly. Sensor installations sometimes yield smaller-thanexpected savings, however, due to factors such as improper product selection or installation, unanticipated interactions with other building components, or failure to adequately consider utility time-of-use rates and demand charges. Users and utility demand-side management (DSM) programs can maximize the performance and cost-effectiveness of sensor installations by considering these issues. Because of the popularity of occupancy sensors and their wide range of application issues, we examine this technology in detail here. Many of the installation issues and economic considerations discussed here also apply to other control technologies.

- Most occupancy sensors turn lights on or off by detecting heat (infrared radiation) or a shift in the frequency of reflected ultrasonic sound waves, or a combination of both. Units that use audible sound or microwaves are also available but are far less common.
- Passive infrared (PIR) sensors are the most common type of signals, and they are able to "see" heat emitted by occupants. Triggering occurs when a change in infrared levels is detected— for example, when a warm object moves in or out of view of one of the sensor's "eyes." PIR sensors are quite resistant to false triggering. Although some PIR sensors have an operating range of up to 35 ft in specific directions and under ideal conditions, they are best used within a 15-ft range for two principal reasons:

7 ENVIRONMENTAL ISSUES

Fluorescent and HID lamps contain mercury, and pre-1980 ballasts contain PCBs as an insulating material. People usually don't consider lamps and ballasts to be potentially hazardous to the environment, and most discarded lamps and ballasts end up in landfills.

7.1 LAMP DISPOSAL

More than 500 million fluorescent lamps and a smaller but significant number of HID lamps are discarded in the U.S. each year. Proper disposal or recycling of these lamps is important, because prior to regulations established in the 1990s they represented the second largest source of mercury in the municipal solid waste stream (5 percent), behind batteries (88 percent). Mercury has been phased out of alkaline batteries, and the development of lowmercury fluorescent lamps and government regulation of the disposal of high-mercury fluorescent lamps has greatly reduced the amount of mercury in the municipal waste stream. However, it is important to understand and follow federal and state regulations regarding disposal of fluorescent and HID lamps to avoid fines and protect the environment.

Although lamps once made up a significant share of the municipal waste stream's release of mercury, other sources contributed a collectively larger amount, including industrial processes, mining, emissions from fossil-fuel-fired power plants, and golf course fungicides. For this reason, proper lamp disposal had historically been a low priority for regulatory agencies. That has changed as state and federal regulators have focused increasing attention on lamp disposal issues with the goal of heading off environmental and health problems.

All fluorescent lamps require some mercury in order to operate. However, they require a much smaller amount of mercury than has historically been added to them during manufacture. A 4-ft T12 lamp needs only 0.1 milligrams (mg) of mercury to operate properly, yet 4-foot T12 fluorescent lamps manufactured in the 1970s typically contained 50 to 100 mg of mercury. Some "excess" mercury is required to replace mercury that is tied up in the glass and phosphor during operation, but the great majority of this "excess" mercury was added to lamps only to accommodate the lamp manufacturing process.

With the introduction of new lamp manufacturing equipment and the advent of new mercury-disposal regulations, lamp manufacturers have been able to reduce the amount of mercury in a typical 4-ft lamp to approximately 5 to 10 mg. To manufacture lamps with mercury at the low end of this range, lamp manufacturers also had to develop new lamp technology to reduce mercury "consumption" by the glass and phosphor. As these mercury consumption technologies improve, we can expect that the quantity of mercury used in fluorescent lamps will continue to decrease toward the theoretical minimum. However, since even low-mercury fluorescent lamps contain mercury, proper disposal is required to protect the environment.

Typically, environmental problems occur when liquid mercury leaches into groundwater or airborne mercury comes down with precipitation. Fish are then exposed to contaminated waters and are eaten by other animals and people. Certain forms of mercury are highly toxic and can cause permanent neurological and kidney damage in wildlife and humans. Even small releases of mercury can cause problems, because the element becomes highly concentrated as it passes up the food chain. In some northern Minnesota lakes with average mercury concentrations of 2 nanograms (ng) per liter, the average concentration in the tissues of mature northern pike reaches 450 ng per gram—a bioconcentration factor of 225,000. This creates a situation in which it may be safe to drink the water from a lake but not safe to eat the fish. This phenomenon has caused some states with large areas of wetlands and lakes to establish strict mercury-disposal regulations. Forty states have issued health warnings banning the consumption of fish from mercurycontaminated lakes.

Mercury poses no threat as long as it is contained in the unbroken lamp. When the lamp gets broken during collection, transportation, or disposal (where many lamps are crushed), the mercury is released. Accidental breakage of a few lamps is unlikely to expose people to significant quantities of free mercury vapor. Potential environmental problems are created when mercury leaches into landfills and is converted by bacteria into volatile forms like methyl mercury or when lamps are improperly incinerated. For these reasons, proper handling and disposal or recycling of lamps has become a major issue.

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