Chapter Eight

Artificial Lighting

It is highly unlikely that daylight alone can satisfy all of the lighting requirements in a building. Certainly, at night there will be a need for artificial light. Also, even during daytime periods when there might be an abundance of external daylight there is likely to be a need for supplementary task illumination. This need for supplementary artificial light occurs in particular in office buildings where deeper rooms cannot be adequately served by windows in side walls. However, notwithstanding these reasons for some form of artificial lighting, the application of good building design practices leading to the exploitation of daylighting opportunities is of paramount importance (Figure 8.1). Artificial light is only the last consideration in a three-tier design approach that commences with the layout of the floor plan, careful consideration of the orientation and shape of spaces, selection of the finishes of the larger surfaces such as ceiling and walls, and then seeks ways of introducing daylight in desirable quantities.

Today, electric light sources constitute the main form of artificial light, although the conversion of electricity into light is by no means efficient. As shown in Figure 8.2 only 7% of the output produced by a standard filament (i.e., incandescent) lamp is in the form of light, while 93% is heat energy. Even fluorescent lamps produce almost twice as much heat as the sun. The situation is exacerbated by the fact that the more efficient electric light sources such as mercury and sodium lamps are mostly unusable because of poor color rendition properties.

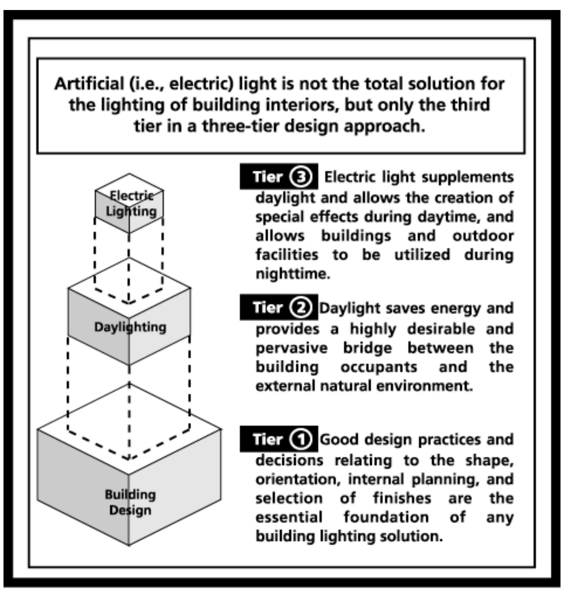


Figure 8.1: Lighting design approach

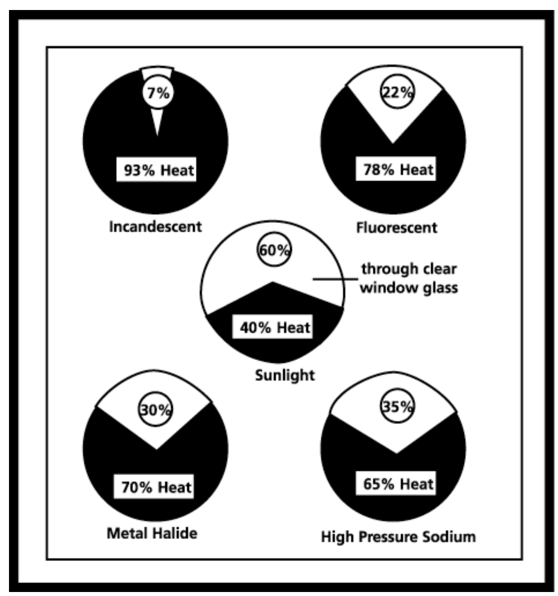


Figure 8.2: Efficiency of light sources

The problems encountered in artificial lighting are often not the same as those encountered in natural lighting. Since both the luminance and location of the lighting installation are easily controlled, it is not a question of providing sufficient light but one of optimizing the visual environment in relation to the discrimination of form, color rendition, work performance, physical comfort and the emotional well-being of the occupant.

8.1 Definition of Terms

In the design of artificial lighting installations, we will be encountering some notions and units of measurement that are derived directly from concepts in the field of physics. One of these units of measurement is the *kilowatt hour (KWH)*. Although this is a Metric unit, it is used internationally as a measure of electric energy consumption. In reference to Figure 8.3, work is performed when a force is applied over some distance. Power is then defined as the amount of work that is performed per unit time and measured in the Metric system in *watt (W)*[1]. Since energy is equal to the amount of power exerted over time, it follows that the Metric unit of electric power is the *kilowatt hour*.

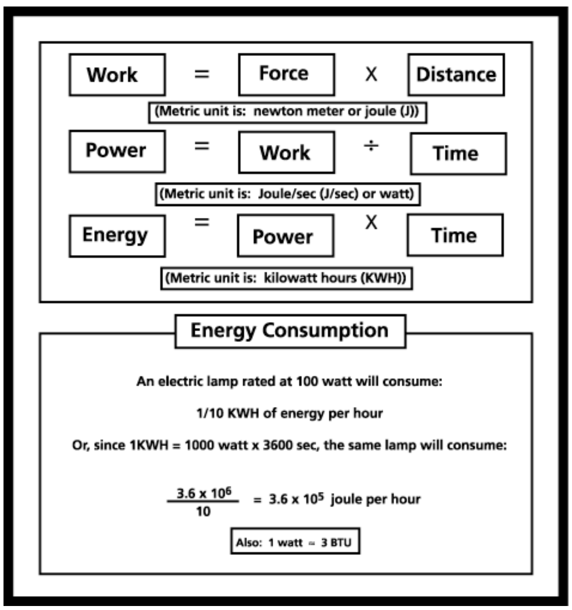


Figure 8.3: Units of electric power and energy

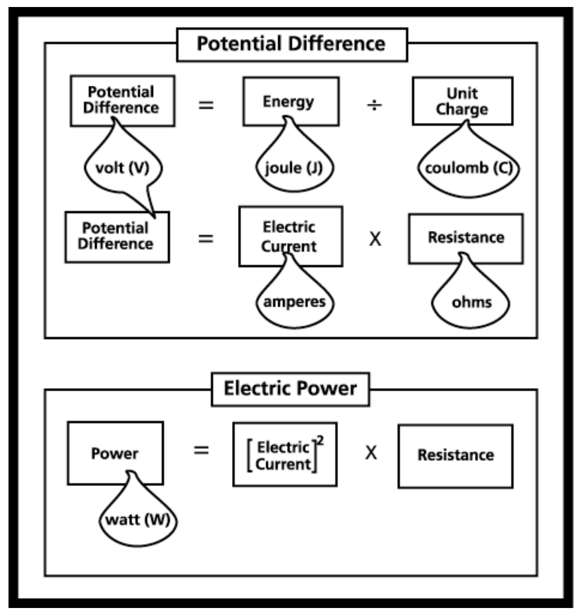


Figure 8.4: Electricity relationships

To fully appreciate the principles of discharge lamps we need to understand the fundamental relationship that exists between the terms electric current, potential difference, and resistance (Figure 8.4). In the physics domain of static electricity, the *energy* in *joules (J)* produced by an electric field is equal to the product of the *potential difference* in *volts (V)* and *unit charge* in *coulombs (C)*. However, for an electric current flowing through a conducting material the *potential difference (volt)* is given by the product of the *current (amperes)* and the *resistance (ohms)*. As shown in the lower part of Figure 8.4, *electric power (watt)* can also be expressed as the product of the square of the *current (amperes)* and the *resistance (ohms)*.

The relationship between *potential difference*, *current* and *resistance* is important in artificial lighting because of the prominent role played by discharge lamps in all interior lighting installations today. These lamps require a high potential difference between two poles to initiate an electric discharge, and then a much lower potential difference to maintain the light producing discharge during the continued operation of the lamp. The variation in potential difference is easily produced with the aid of an electric transformer that produces the desired potential difference by first increasing and then throttling back the electric current.

[1] It is of interest to note that one *watt* of power is equivalent to about 3 BTU of heat in the American system of units.

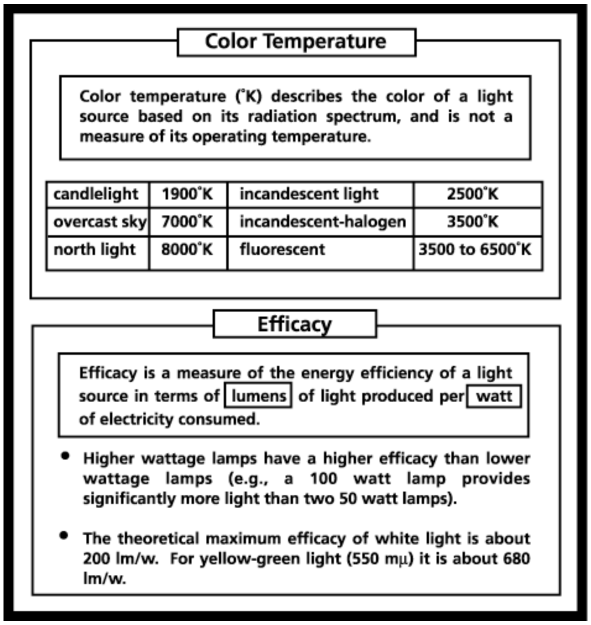


Figure 8.5: Color Temperature and Efficacy

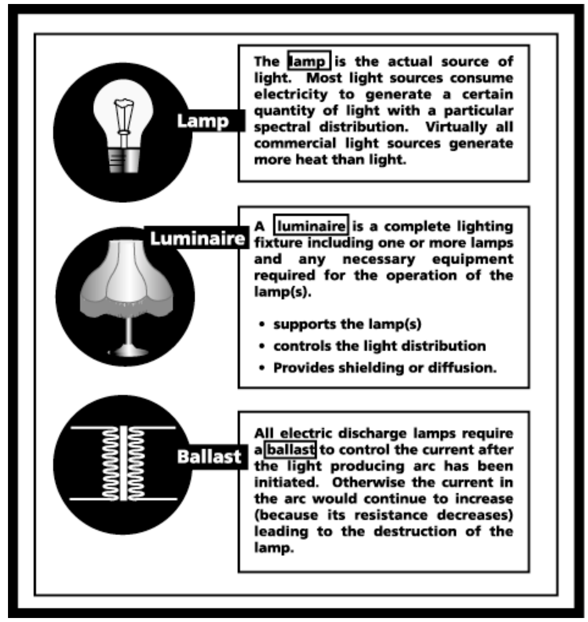


Figure 8.6: Lamp, Luminaire, and Ballast

The concept of *color temperature* was explained in some detail previously in Chapter 7. It will therefore suffice here to only briefly reiterate that the term *color temperature* is used to describe the color spectrum emitted by a light source. The reason why the color spectrum is expressed in terms of a temperature is because in this way it can be compared to the emission characteristics of a *black body* when it is heated. Although a *black body* is an idealized concept in physics that does not actually exist, it is most useful because it allows the spectrum of wavelengths that is emitted at different temperatures to be mathematically calculated. The fact that *color temperature* is unrelated to the operating temperature of a light source is evident in the table of the *color temperature* of different natural and artificial light sources shown in Figure 8.5. An overcast sky, which is quite cool, has a color temperature of 7000 K while an incandescent lamp, which is too hot to touch, has a color temperature of only 2500 K.

The term *efficacy* is used to describe energy efficiency in terms of the light flux produced (lumens) per electric power (watt) consumed. The unit of efficacy is therefore *lumen/watt (lm/W)*. As indicated in Figure 8.5 higher wattage lamps have a higher efficacy than lower wattage lamps. Therefore, a 200-watt lamp provides significantly more light than four 50 watt lamps. Also, there exists a theoretical maximum efficacy for light depending on the spectral distribution. It is about 200 lm/W for white light and over 600 lm/W for yellow-green light due to the greater sensitivity of the eye to the 550 mμ wavelength.

Finally, we need to be familiar with the terms that are used to describe the artificial light fixture itself (Figure 8.6). The term *luminaire* applies to an entire fixture, which includes one or more *lamps* (i.e., the actual light source), the accessories that are required to hold and operate the lamp, and any device that is used to control the distribution of light such as a lamp shade. As mentioned previously, discharge lamps require an electrical transformer capable of generating the initial potential difference that is required to initiate the discharge of ions between the anode and cathode of the lamp. This transformer is referred to as *ballast*.

8.2 Creation of Light Artificially

Let us for a moment reconsider the principle of *black body* radiation discussed earlier in connection with color temperature. A *black body* consists of an ideal material that absorbs all electromagnetic radiation, including light, falling upon it. If this idealized *black body* is heated it will emit radiation of a wavelength directly related to the temperature of the body. The quantity of radiation produced is not the same at all wavelengths, but rather the radiation spectrum resembles a skewed Normal Distribution Curve with the peak of the curve moving to the left as the temperature of the black body increases.

Figure 8.7 shows the distribution of power in the spectrum of a black body radiator. Not only are the curves for higher temperatures always above the curves for lower temperatures, but also the peaks (i.e., maxima) of the curves are displaced toward the shorter wavelengths as the temperature is increased. However, while it is clearly shown in Figure 8.7 that a black body would produce a maximum amount of light if it were to be heated to 6000 K, this does not mean that any other material heated to that temperature will produce a maximum amount of light or any light at all, for that matter. We must remember that a black body is an idealized material that does not actually exist. It must be stressed again that the operating temperature of a lamp is distinct from its color temperature. In other words, an artificial light source operating at a temperature of 100ºF may produce much more light than one operating at a temperature of 200ºF.[2] A black body radiator simply provides a convenient standard for comparing the radiation spectrum emitted by a lamp (i.e., the color rendition characteristics of the lamp).

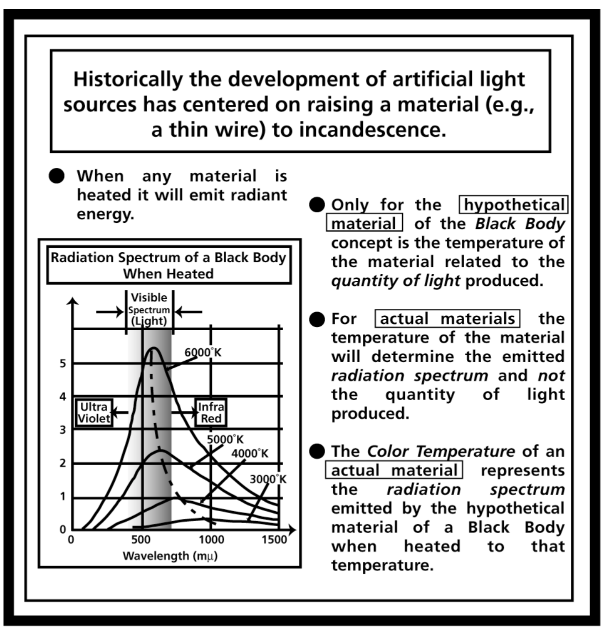


Figure 8.7: Black Body radiation spectrum

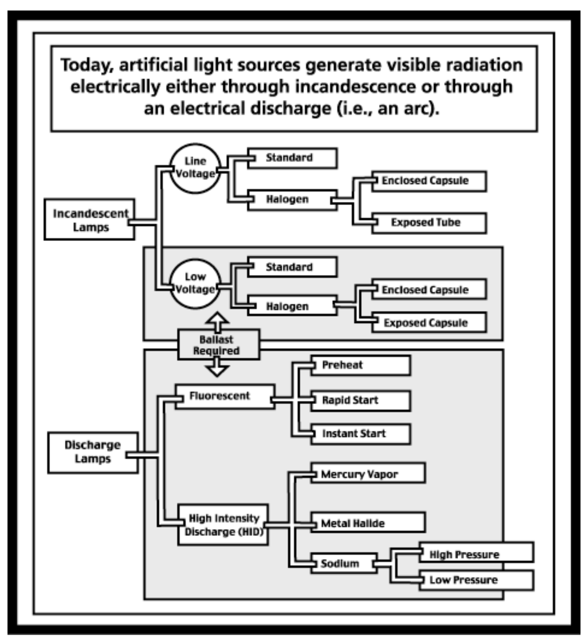


Figure 8.8: Artificial light sources

The principal artificial light sources used in buildings today are electrical in nature. They fall into two distinct categories, namely incandescent lamps and discharge lamps (Figure 8.8). While there are only two kinds of incandescent lamps, there are several types of discharge lamps subject to the

2 It should also be noted that the operating temperature of a lamp is measured in ºF or ºC, while its color temperature is measured in K.

environment within which the electrical discharge takes place. If we are to compare these different artificial light sources it is necessary to establish some criteria by which the characteristics of a light source may be assessed. Cost, color, and utility would appear to provide the essential elements for such a comparison.

Capital costs and operating costs are determined by the luminous efficiency or efficacy (i.e., lumens per watt of power consumed), the lumen maintenance (i.e., lumen output during the operational life-cycle), the initial capital cost of the lamp installed in a luminaire, and the useful life of the lamp. As shown in Figure 8.9 the life-span of different kinds of lamps varies greatly, with discharge lamps exceeding the life-span of incandescent lamps by a factor of five to 10. Among discharge category, with the exception of Metal Halide lamps, the High Intensity Discharge (HID) lamps typically have by far the longest life-span. However, the ability to operate for long periods before failure is not the only measure of efficiency. The useful life of a lamp is governed also by the capacity of the lamp to maintain its initial luminous efficiency over its life-span. As will be seen later in Figures 8.18 and 8.21, the *depreciation* of lamps varies from an average of about 15% to a high of 30% in the case of some Metal Halide lamps.

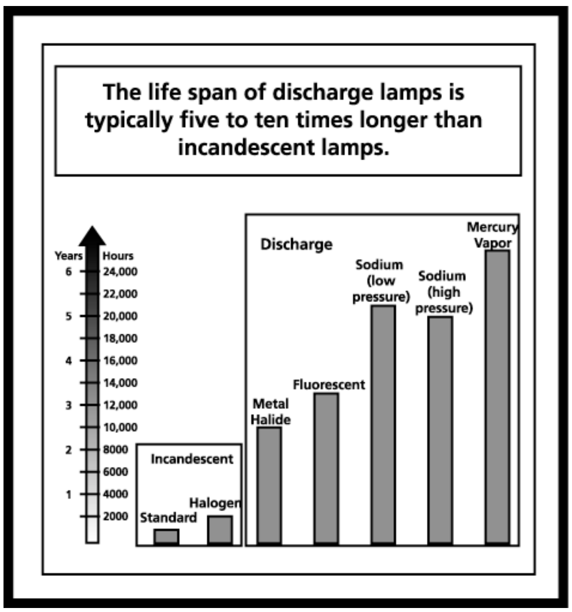


Figure 8.9: Average life-span of lamps

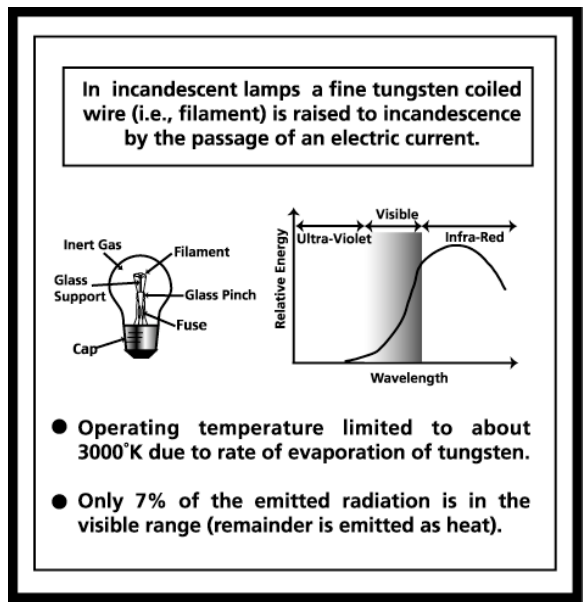


Figure 8.10: The incandescent (filament) lamp

The color rendering properties of a lamp are normally considered to be more important than the actual color of the source. Since the appearance of a colored surface exposed to a light source is governed primarily by the spectral distribution of the light emitted, the radiation spectrum will serve as a useful guide to the color rendering properties of a lamp. It is unfortunate that in addition to the fact that more than 60% of the energy output of all electric light sources is heat and not light (Figure 8.2), the more efficient lamps have the poorest color rendition properties.

Finally, the utility or practical convenience of a lamp is governed by a number of physical and operational characteristics such as its size, shape, wattage range, and need for auxiliary equipment.

Incandescent (filament) lamps: In these lamps a fine tungsten wire, referred to as the filament, is raised to incandescence by the passage of an electric current. With a *color temperature* of around 3200˚K over 90% of the radiation is in the infra-red region (Figure

8.10). Evaporation of the filament results in the familiar blackening of the bulb and ultimately causes the tungsten wire to break. Tungsten is normally chosen for the filament material because of its high melting point and slow rate of evaporation. Since higher operating temperatures will produce greater efficiency in incandescent lamps, it is to be expected that higher wattage units with thicker filaments will be more efficient than lower wattage lamps. In fact, a single 100-watt filament lamp will be some 5 lm/W (i.e., 30%) more efficient than two 50 watt lamps. Accordingly, the design operating temperature of a filament lamp will be very much a compromise between life-span and efficiency based on the following approximate relationship:

life span of lamp = 1 / (luminous efficiency)^6 (HRS) …………………… (8.1)

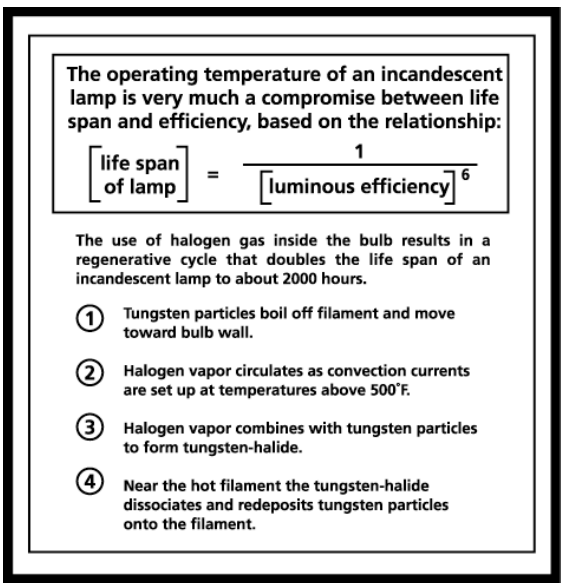


Figure 8.11: The halogen regenerative cycle

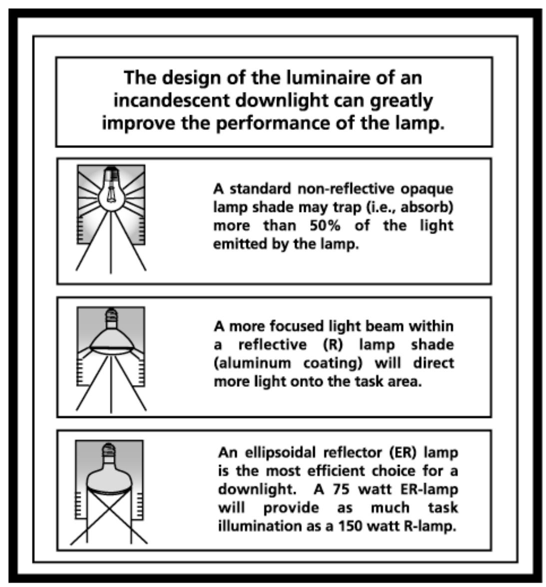


Figure 8.12: Luminaire considerations

Fortunately, the rate of evaporation of the tungsten filament can be reduced by raising the vapor pressure of the gas in the lamp. Most commonly the gas used is a mixture of argon and nitrogen, although it has been shown that halogen gas (i.e., iodine, chlorine, bromine, or fluorine) will set up a regenerative cycle (Figure 8.11). In tungsten-halogen lamps the evaporated tungsten associates with the halogen to form tungsten-halide vapor, which dissociates when diffused back to the hot filament thereby re-depositing tungsten on the filament. This regenerative cycle enables the filament to operate at slightly higher temperatures, with a resulting increase in efficiency and a service life of up to 2000 hours with little fall-off in lumen maintenance.

There are two further problems associated with the large amount of radiation emitted by filament lamps in the infra-red region of the spectrum (Figure 8.10). Not only is up to 93% of the input energy wasted for purposes of lighting, but the resultant heat radiation may substantially increase the temperature of the building environment, in particular when very high levels of illumination (e.g., hospital operating theaters) are required. Furthermore, since the color rendering properties of a lamp are very much affected by its spectral distribution, incandescent lamps will tend to soften the appearance of colored surfaces by virtue of their predominant infra-red radiation. Even though the color rendering characteristics of these lamps are by no means true nor similar to daylight, they are commonly accepted as being pleasant and flattering.

From a more general versatility point of view incandescent lamps are convenient to use because they provide instantaneous light, require no auxiliary equipment, and are available in a very large range of wattages, shapes, and sizes. As shown in Figure 8.12, the choice of luminaire can greatly influence the ultimate light output of an incandescent lamp. This is particularly true for *direct lighting* fixtures (Figure 8.25) in which virtually all of the light is directed downward. The strategies commonly used by the manufacturers of such light fixtures to minimize the absorption of light by the inside surface of the lamp shade include: a highly reflective metal surface finish (e.g., aluminum coating); a more focused light beam produced by a lamp unit with its own encapsulated reflective surround; and, an ellipsoidal reflector (ER) lamp that utilizes a lens to produce a sharply defined parallel light beam.

Discharge lamps: In all discharge lamps light is produced by the passage of an electric current through a gas or vapor. High Intensity Discharge (HID) lamps such as the high-pressure mercury vapor lamp (Figure 8.14) consist essentially of an arc tube with electrodes at both ends, containing a small quantity of mercury in combination with a low-pressure rare gas such as argon. It is the function of the rare gas to facilitate initiation of the discharge. However, the presence of the rare gas will serve little purpose unless a very large potential difference is first created electrically. For this reason, the mercury vapor lamp, like all discharge lamps, requires a choke circuit and incorporates its own starting electrode.

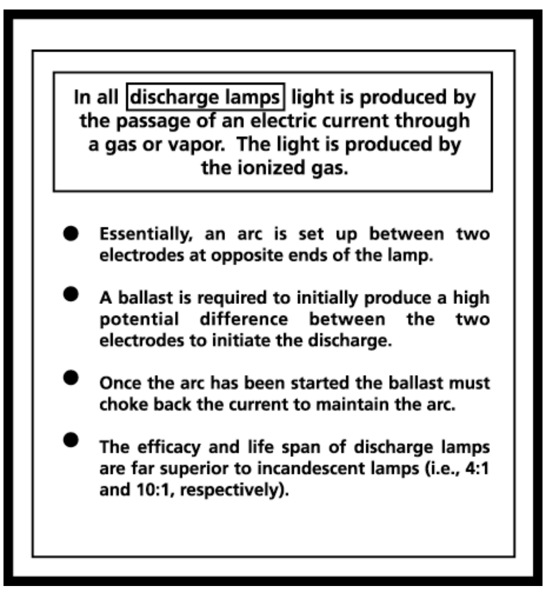


Figure 8.13: Discharge lamp principles

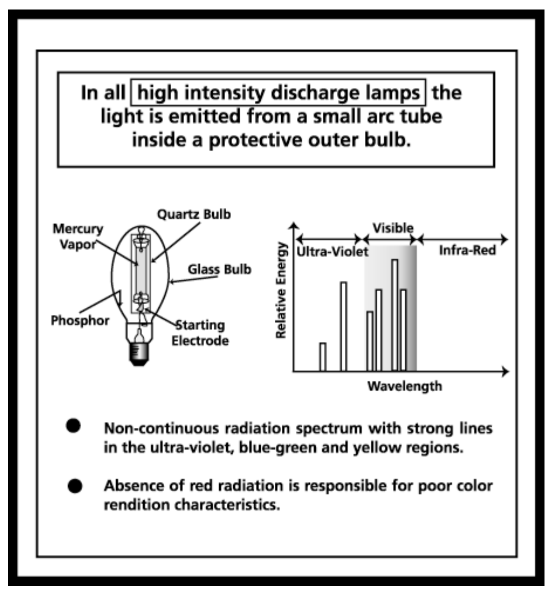


Figure 8.14: High Intensity Discharge lamps

Although there are several types of discharge lamps that are basically distinguished by their operating pressure, in all of them a discharge is initiated in the filling gas accompanied by a low brightness glow. In other words, it may take some time for the lamp to attain its full light generation capacity. For example, in the case of the high-pressure mercury lamp, as the mercury vapor pressure builds up a narrow, bright arc develops over a period of several minutes along the center of the arc tube. As shown in Figure 8.14, the emitted radiation spectrum displays strong lines in the ultra-violet region, while distribution in the visible region comprises separate lines in the blue-green and yellow wavelengths. The lack of red radiation is responsible for the poor color rendition, but at the same time allows a higher luminous efficiency.

The color rendition characteristics of the high-pressure mercury lamp can be improved in two ways: first, by coating the inside surface of the bulb with a phosphor such as magnesium fluorogermanate or yttrium vanadate (the phosphor coating is capable of reradiating some of the ultra-violet wavelengths into the visible range); and second, by adding metal halides into the discharge tube (through the introduction of metallic vapors such as iridium iodide). In the latter case, while the resulting metal halide lamp displays a continuous radiation spectrum in the visible range it is by no means evenly distributed (Figure 8.15).

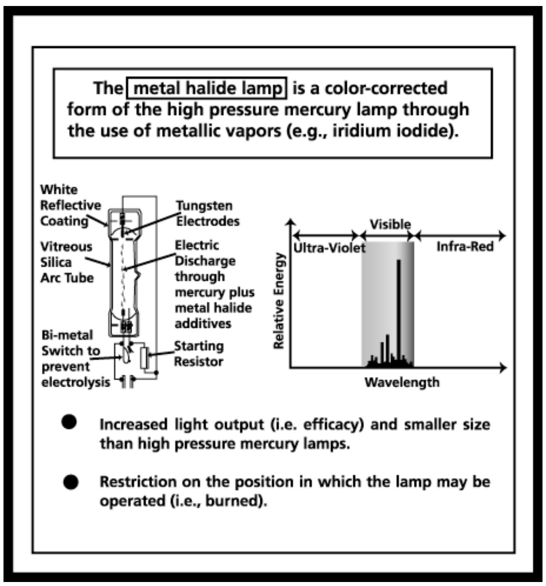


Figure 8.15: The metal halide lamp

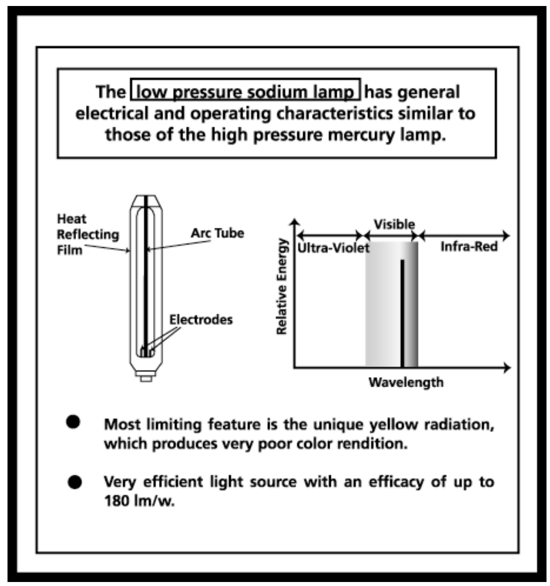


Figure 8.16: The low pressure sodium lamp

Although the color rendition properties of the high-pressure mercury lamp in the uncorrected form may be acceptable for exterior lighting and some high-bay industrial applications, this lamp is normally not considered for interior lighting. The metal halide lamp, on the other hand, is much more acceptable for external and high-bay interior lighting.

The low-pressure sodium lamp (Figure 8.16) is a very efficient light source capable of producing up to 150 lm/W. Since it is also a discharge lamp it has general electrical and operating characteristics similar to those of the mercury lamp. The most limiting feature of the sodium lamp is its unique yellow radiation, which is responsible for high luminous efficiency but very poor color rendition. This is most unfortunate, since the sodium lamp has the highest efficacy of all currently available electric light sources. For this reason, it is understandable that considerable efforts have been made by manufacturers to improve the color rendition performance of the sodium lamp.

It was found that the color rendition properties of the sodium lamp can be improved by operating the lamp at above atmospheric pressure. However, the ability to do this has been restricted in the past by the lack of an enclosure capable of containing the chemically active hot sodium. This problem has now been overcome by the development of crystalline alumina. Accordingly, high pressure sodium lamps with crystalline alumina enclosures produce white light at a reduced efficiency of about 110 lm/W (Figure 8.17). Application of this modified sodium lamp is found in outdoor street lighting and to a lesser extent in the lighting of high bay industrial interiors.

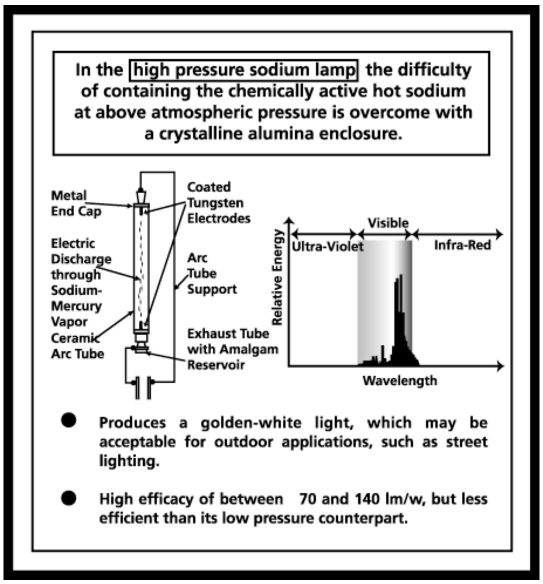
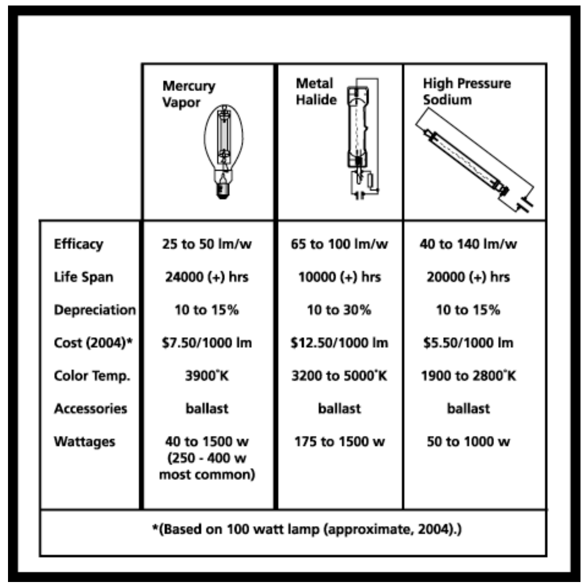


Figure 8.17: The high-pressure sodium lamp



	Mercury Vapor	Metal Halide	High Pressure Sodium
Efficacy	25 to 50 lm/w	65 to 100 lm/w	40 to 140 lm/w
Life Span	24000 (+) hrs	10000 (+) hrs	20000 (+) hrs
Depreciation	10 to 15%	10 to 30%	10 to 15%
Cost (2004)*	$7.50/1000 lm	$12.50/1000 lm	$5.50/1000 lm
Color Temp.	3900˚K	3200 to 5000˚K	1900 to 2800˚K
Accessories	ballast	ballast	ballast
Wattages	40 to 1500 w (250 - 400 w most common)	175 to 1500 w	50 to 1000 w

*(Based on 100 watt lamp (approximate, 2004).)

Figure 8.18: Comparison of mercury vapor, metal halide, and high-pressure sodium lamps

A comparison of mercury vapor, metal halide, and high-pressure sodium lamps (Figure 8.18) indicates that all three of these high intensity discharge lamps require a ballast to produce the high potential difference that is required to produce the initial discharge. While the life-span of the metal halide lamp is over 10,000 hours, it is less than half that of the other two lamps at more than twice the capital cost.

Fluorescent lamps: The fluorescent lamp basically utilizes a low-pressure mercury discharge. At the low operating pressure (i.e., approximately 0.00015 psi) more than 95% of the radiation emitted is outside the visible spectrum in the ultra-violet region (Figure 8.19). Some 25% of this ultra-violet radiation is reradiated into the visible range by a fluorescent powder (i.e., phosphor) coating on the inside of the enclosing tube.

The major difference between the light from a fluorescent lamp and a high-pressure mercury lamp is that the former produces a continuous spectrum. Furthermore, the color rendition properties of the fluorescent lamp can be partly controlled by the precise consistency of the phosphor film. This has resulted in a range of fluorescent lamps being commercially produced for different lighting purposes (Figure 8.20).

Since fluorescent lamps are discharge lamps, they require a ballast to provide a high starting voltage (i.e., potential difference) to initiate the discharge. The switch circuit is one of the simplest and most reliable circuits even though it suffers from the disadvantage of a small-time delay before starting. In the transformer circuit this disadvantage has been eliminated at a slightly increased cost.

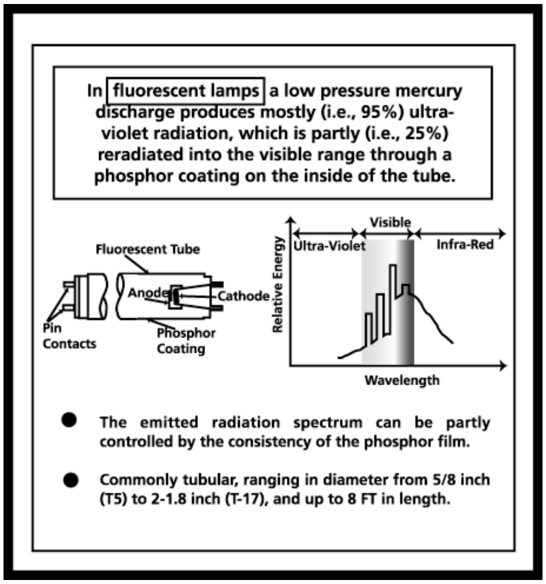


Figure 8.19: The fluorescent lamp

Fluorescent Lamps are available in a wide range with varying color rendition properties.

Lamp Designation	Color of Emitted Light	Color Rendition Characteristics	
"Daylight"	blue-white	FAIR:	unflattering to skin and warm tones
"Cool White"	white with blue tint	GOOD:	blends with daylight
"Warm White"	yellow-white	FAIR:	blends well with light from filament lamps
"Soft White"	white with pink tint	GOOD:	enhances warm tones and flattering to skin
"Cool Deluxe"	white	EXCELLENT:	best color rendition available
"Warm Deluxe"	white	GOOD:	creates warm atmosphere and flattering to skin
"Natural White"	white with pink tint	EXCELLENT:	very good color rendition in warm atmosphere
"White"	white with yellow tint	FAIR:	may be used interchange-ably with "warm white" or "cool white"

Figure 8.20: Color rendition properties of fluorescent lamps

Since the emission of short-wave radiation (i.e., ultra-violet) is related to the vapor pressure inside the lamp, which in turn is affected by the ambient temperature, it is understandable that the light output of a fluorescent lamp will vary with the surface temperature of the tube. A fall-off in light will occur in excessively hot (e.g., 20% at 140˚F) or cold temperatures. In cold stores it is normal practice to enclose fluorescent tubes in larger acrylic casings for insulation purposes. Apart from this, ambient temperature will affect the starting condition, although a switch start circuit tends to overcome most of these problems. A more serious limitation of fluorescent lamps is the restricted wattage range commercially available (i.e., typically 40, 80, and 125 watt). Lower wattage lamps tend to have reduced luminous efficiency while 200 watt represents a practical upper limit at this stage of the technical development of fluorescent lamps.

In recent years, due to an increasing need and desire for energy conservation, many incandescent lamps have been replaced with fluorescent lamps. This has been a relatively simple matter in the case of public and commercial office buildings where the length of fluorescent tubes did not present an obstacle for the background illumination provided by ceiling and cornice lighting. However, a similar replacement of incandescent lamps in desk lamps had to wait for the development of compact fluorescent lamps. In these lamps the traditional long tube has been literally folded into an assembly of multiple smaller diameter short tubes that can readily fit into a normal incandescent light fixture.

Figure 8.21 clearly shows the superior performance of both types of fluorescent lamps over the incandescent lamp in respect to efficacy and life-span. The only advantages of the incandescent lamp are its simplified operating environment (i.e., neither a ballast nor any special electrical circuit is required) and its very wide range of wattages. However, the initial acquisition cost of the compact fluorescent lamp is still more than five times the cost of an incandescent lamp and almost eight times the cost of an equivalent fluorescent tube.

	Incandescent Lamp	Fluorescent Tubular	Fluorescent Compact
Efficacy	17 to 38 lm/w	40 to 90 lm/w	26 to 61 lm/w
Life Span	1000 to 2000 hrs	13000 hrs	10000 hrs
Depreciation	10 to 20%	10 to 15%	10 to 15%
Cost (2004)*	$2.00/1000 lm	$1.50/1000 lm	$11.00/1000 lm
Color Temp.	2100 to 3300˚K	2500 to 7500˚K	2700 to 5000˚K
Accessories	none	ballast	ballast
Wattages	wide range	limited	limited

*(Based on 100 watt lamp (approximate, 2004).)

Figure 8.21: Comparison of incandescent and fluorescent lamps

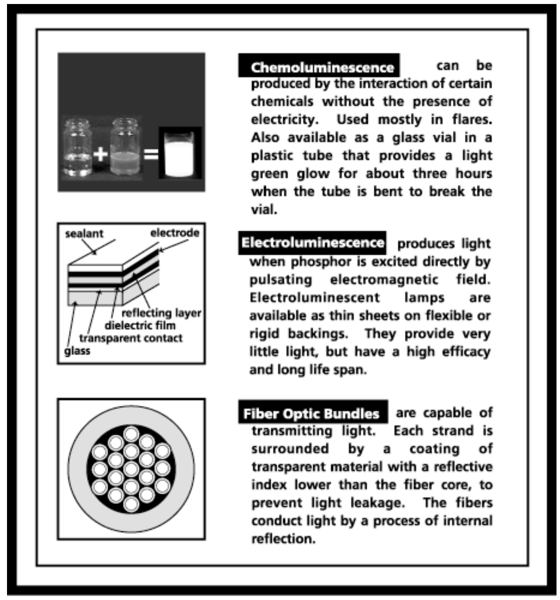


Figure 8.22: Other potential light sources

Other light sources: Although light sources base on the discharge principle are likely to retain their dominant position in the market place for some time to come, there are other sources of light with varying application potential (Figure 8.22). Foremost among these are electroluminescent lamps. While fluorescent lamps produce light indirectly through the excitation of phosphors, electroluminescent sources produce light directly from electric energy produced by an applied voltage. Although present applications of electroluminescent lamps in the form of Light Emitting Diodes (LED) are still limited they show great promise for the future in terms of life-span (over 40,000 hours) and efficacies in the vicinity of 100 lm/W (see Chapter 12, Section 12.5.4).

Neon lamps, which are used extensively in advertising, consist of an evacuated glass tube filled with ionized neon gas. By means of a transformer capable of increasing the normal 115-volt input voltage to around 8000 volts, an electric current is passed through the ionized gas in the tube. The essentially red light produced in this manner may be changed in several ways: by varying the gas pressure; by mixing the neon gas with helium; or, by using colored glass tubing. The efficiency of the neon lamp is rather low, in the region of 5 lm/W.

Will industry be able to make more headway in harnessing the light produced by chemical reactions? Currently the exploitation of chemiluminescence is limited to flares and glass vials in plastic tubes that provide a green glow for a few hours when the tube is bent to break the vial.

Fiber optic bundles are capable of transmitting light with a somewhat limited efficiency by a process of internal reflection. This would potentially allow the transmission of direct sunlight or perhaps some high intensity artificial light source (e.g., laser light) to be transmitted through ducts into building spaces. Some assemblies of this type that transmit direct sunlight into windowless interior spaces have been commercially available for several years. However, they have not found widespread application to date.

Color adaptation, although not as prominent a factor in lighting design as the adaptation to brightness, is nevertheless a condition that needs to be taken into account in the design of artificial lighting installations. Specifically, there are two factors to consider:

- Different kinds of artificial light sources may vary widely in respect to their color rendition characteristics. For example, the low-pressure sodium lamp reduces all colors to shades of grey-brown, the mercury vapor lamp will over-emphasize yellow and convert red to brown, While the incandescent lamp will brighten yellow, orange and red and therefore tend to dull blue and green.
- The perception of color is very much related to the background color and luminance. For example, if an entire wall is covered with a particular color, the eye will adapt and the color will seem less saturated. A pink carpet in a room with pink walls will be less prominent, or perhaps offensive, than if the walls have been painted white or cream.

Although the human eye will make a considerable effort to adapt to the color rendition characteristics of a particular artificial light source, it cannot compensate for serious deficiencies in the radiated spectrum. Accordingly, the success of an artificial lighting installation may be gauged in part at least by its ability to provide satisfactory perception of the surface colors in the space. One practical lesson to be learned from this is that any color scheme for a building space should be chosen under the light source by which it will normally be seen, and if possible, under the same background conditions.

8.3 Functions of the Luminaire

Since light travels in a straight line, it is possible to specify light distribution in terms of intensity and direction alone. Polar diagrams provide a means of presenting graphically, in terms of polar coordinates, the luminous intensity distribution of a given light source or luminaire. As shown in Figure 8.23, the luminaire is considered to be at the point of intersection of radial lines normally representing directions in the vertical plane. Concentric circles provide a scale of luminous intensity expressed in candelas.

On this grid of intersecting radial lines and concentric circles the luminous intensities of a particular luminaire are plotted in each direction. The resultant polar curve represents the intensity distribution in the plane under consideration. If the distribution is symmetrical about a vertical axis, as is the case with incandescent installations, one diagram will be representative of the distribution in all vertical planes. In the case of fluorescent luminaires, the polar diagrams in other planes will be required for full information, although often one average curve will suffice.

The information that can be obtained from a polar diagram is twofold. First, it provides numerical values of the luminous intensity in any direction on one plane. Second, it provides much qualitative information about the properties of a luminaire. By viewing a polar diagram, we can differentiate at a glance between various types of luminaires such as direct, indirect, and so on. However, we cannot determine from the polar diagram whether one luminaire produces more light flux (i.e., lumen) than another, because the flux emitted in a given direction is not directly proportional to the intensity in that direction. Accordingly, the area enclosed by a particular polar curve does not provide any indication of the amount of luminous flux emitted by that light source. It simply indicates the distribution of the light emitted.

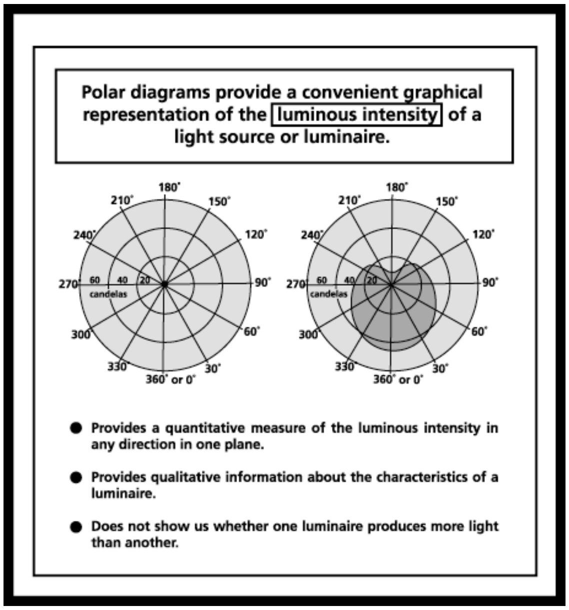


Figure 8.23: Polar diagrams

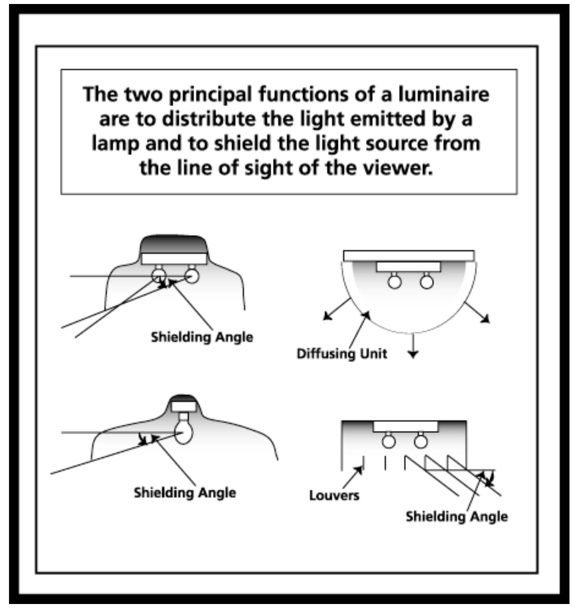


Figure 8.24: Shielding the eyes

As discussed previously in Section 8.1, a luminaire is defined as a complete, fixed or portable lighting unit including one or more lamps and any associated equipment required for its operation. However, it does not include any permanent parts of a building such as a ceiling or structural element. There are basically three functions that a luminaire must perform:

1. It must support and possibly protect the lamp. In the case of some artificial light sources, such as for example metal halide lamps (Figure 8.15), the luminaire must hold the lamp in a particular operating position.
2. It must control the distribution of light from the lamp by directing the light flux where it is required.
3. It must provide some form of control over the luminance of the source in order to prevent glare. This control may be in the form of shielding or diffusion.

Since glare is caused mainly by the existence of a direct line of vision between the observer and a source of high luminance, it is normal practice to restrict or limit luminance in the immediate visual field. For this reason, artificial lighting codes will prescribe shielding angles and a maximum luminance. While for most industrial installations it will be possible to provide adequate shielding by means of metal troughs, in the case of fluorescent units containing more than one tube, troughs would need to be excessively deep and therefore louvers are used. In the latter case the calculation of the shielding angle is based solely on the geometry of the louver grid (Figure 8.24). The addition of louvers will naturally tend to constrict the light distribution resulting in the need for closer spacing of luminaires generally. Sometimes the louver blades themselves will constitute a source of glare. This may be due to over-brightness of the source or a high reflectance blade finish, or both. In either of these cases, it is normally sufficient to darken or otherwise reduce the reflectance of the louver blades.

A wide variety of luminaires are commercially available for the lighting designer to choose from. They are essentially distinguished by the proportion of light that they direct downward to the work plane and upward to the ceiling. The greater the proportion of light aimed upward and then reflected downward by the ceiling the more diffuse the lighting environment will be. If most of the light is directed downward then shadows will be distinct, accentuating the three-dimensional nature of the objects in the building space.

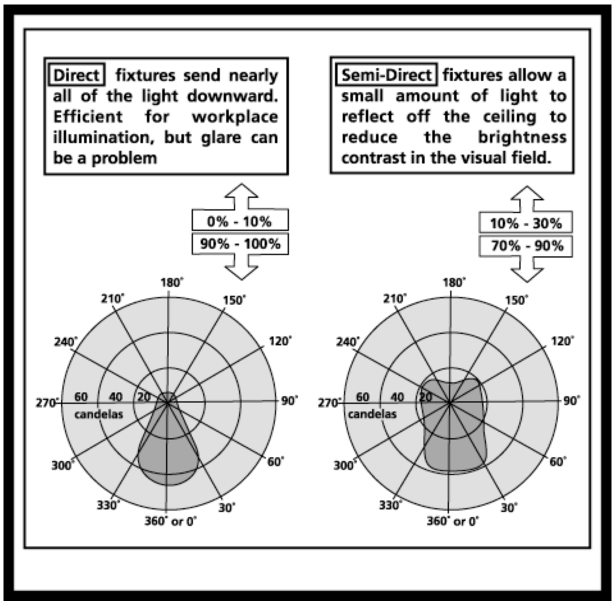


Figure 8.25: Direct and semi-direct luminaires

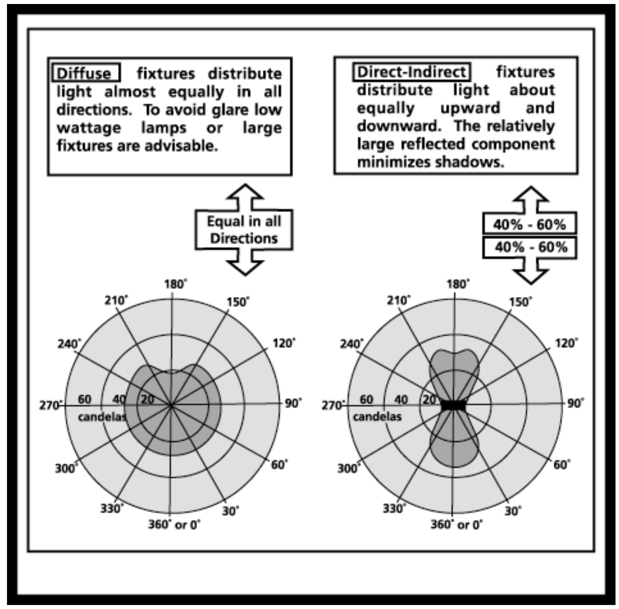


Figure 8.26: Diffuse and direct-indirect luminaires

Direct luminaire: Practically all of the light is directed downward, resulting in a low vertical surface illumination (Figure 8.25). Direct luminaires are normally used for individually controlled task lighting in combination with a general background lighting system.

Semi-Direct luminaire: Similar to the direct-indirect system, although the ceiling light component is small. Therefore, the room will lack diffuseness, possibly resulting in annoying shadows if the number of fixtures per ceiling area is small (Figure 8.25).

Diffuse luminaire: The diffuse system provides light approximately equally in all directions (Figure 8.26). The distance between the luminaire and the ceiling should be sufficient to avoid excessive ceiling brightness.

Direct-Indirect luminaire: Provides approximately equal distribution of light upward and downward (Figure 8.26). Can be a very successful lighting system, due to the fact that it provides a bright ceiling and yet provides up to 50% direct lighting. Accordingly, there is little likelihood of any problems arising due to brightness differences between the background and the task area.

Semi-Indirect luminaire: Similar to the indirect system except that the shade is translucent, thus allowing about one third of the light to fall directly into the room (Figure 8.27). Nevertheless, the ceiling remains the main radiating source.

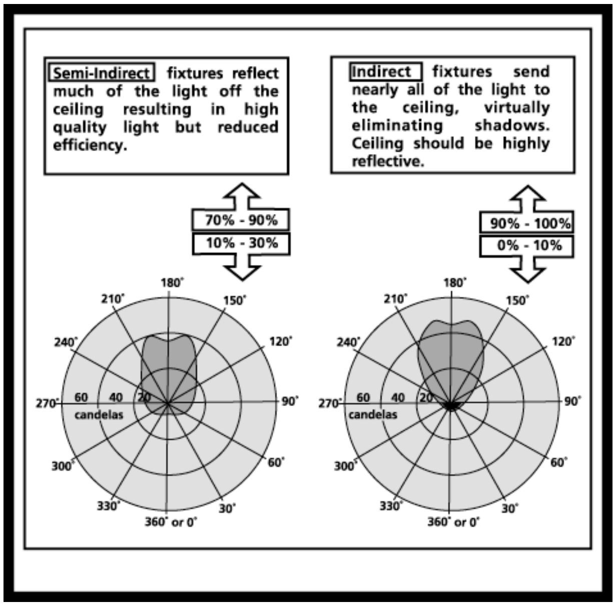


Figure 8.27: Semi-Indirect and Indirect luminaires

Luminaire Classification	Typical Distribution Upward	Typical Distribution Downward	Luminaire Features and Application
DIRECT	0%	100%	Closed top metal reflector or recessed trough for task lighting.
SEMI-DIRECT	20%	80%	Metal reflector with large slots at the top or diffuser type fluorescent fixtures.
DIFFUSE	Equal in all directions		Opal glass enclosed diffuser for incandescent lamps.
DIRECT-INDIRECT	50%	50%	Opaque cylindrical shade with open ends.
SEMI-INDIRECT	80%	20%	Incandescent and fluorescent units with open top and diffuse underside.
INDIRECT	100%	0%	Coves and cornices or suspended fixtures with open tops and closed undersides.

Figure 8.28: Comparative analysis of luminaires

Indirect luminaire: Nearly all the light output is directed to the ceiling and upper walls of the room (Figure 8.27). The ceiling and upper wall sections in effect become a secondary light source, and if these surfaces have similar reflections, then the room illumination will be diffuse and devoid of shadows.

When recessed luminaires are used the ceiling will receive reflected light only and will therefore tend to be the darkest part of the room. The resultant brightness ratio between the luminaire and ceiling is likely to be high and therefore unsatisfactory in any but the smallest rooms, where the general illumination level is expected to be high if the wall and ceiling surfaces are light colored. To achieve a comfortable brightness balance in building interiors it is common practice to limit brightness ratios between areas of unequal illumination level. As discussed previously in Section 6.6, maximum brightness ratios are suggested as follows:

Ratio of task to surround ……………………………………… 3:1
Ratio of task to remote background ………………………….. 5:1
Ratio of luminaire to surround ……………………………….. 15:1
Maximum brightness ratio anywhere ………………………… 35:1

It is therefore implied that an artificially lit interior will incorporate either general or local lighting, or more often than not both of these. General lighting schemes are designed to provide uniform illumination (often of a diffuse nature) over a hypothetical horizontal plane extending throughout the entire space. This may be achieved by a pattern of ceiling fittings or a continuous luminous ceiling. Local lighting, on the other hand, is intended to provide high levels of illumination over relatively small areas, such as work benches and machinery. Luminaires for local lighting are best located immediately above the work plane with the light directed to the task area.

8.4 Light Fixtures

Apart from the boundless variety of commercially available mostly stand-alone luminaires that are either directly connected to the electrical wiring of the building and operated through a remote switch (e.g., a ceiling-mounted diffuse luminaire) or fitted with an electrical cord that can be conveniently plugged into an electrical receptacle (e.g., a desk lamp), there are a number of more or less built-in light fixtures. These fixtures typically form part of the building itself and are normally neither portable nor removable without at least some minor form of renovation or reconstruction.

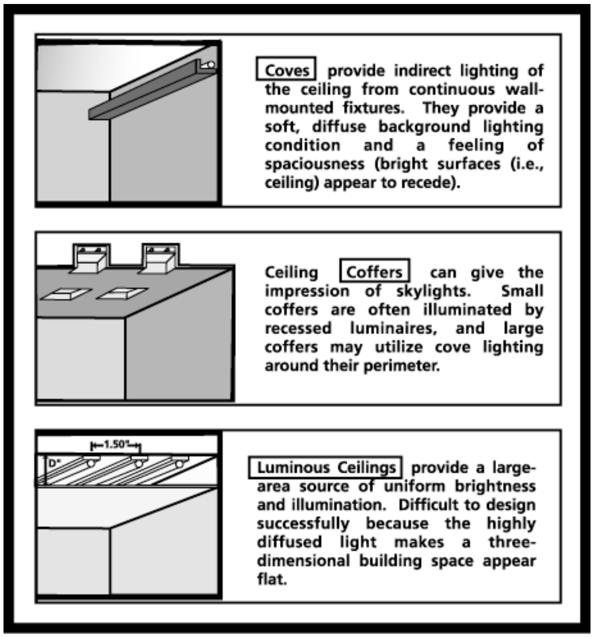


Figure 8.29: Coves, coffers and luminous ceilings

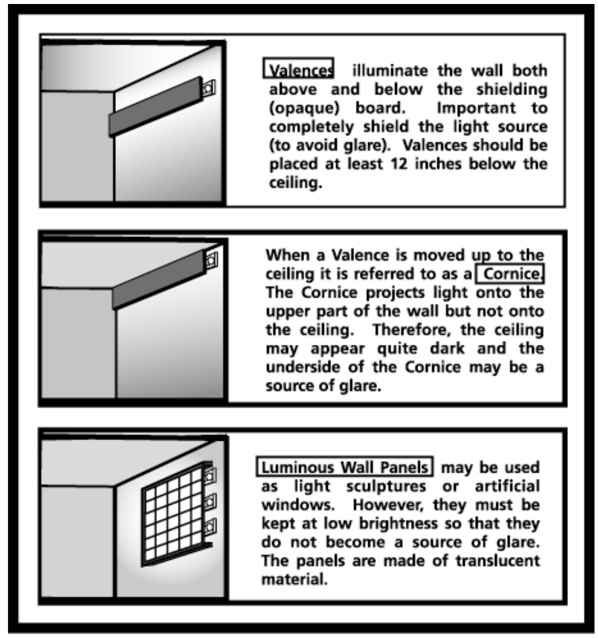


Figure 8.30: Valences, cornices and luminous wall panels

Coves are normally located along part or the entire length of a wall, just under the ceiling as shown in the top section of Figure 8.29. Since virtually all of the light that they produce is reflected from the ceiling, the quality of light will be diffuse and the brighter ceiling will endow the room with a feeling of spaciousness.

Coffers are typically recessed into the ceiling (mid-section of Figure 8.29) and could be categorized as artificial skylights. However, because of the limitations of artificial light sources the light produced is of course far less intense than a normal skylight, particularly under clear sky conditions. Therefore, whereas a single skylight is usually sufficient to light an entire room during daytime hours, several coffers would be required to provide adequate light during nighttime.

Luminous Ceilings (bottom section of Figure 8.29) have become less popular in recent times due to the need for energy conservation. Also, the diffuse nature of the light produced by a luminous ceiling tends to create a somewhat drab environment that is devoid of shadows unless other directional sources of light are added.

Valences are similar to coves with one major difference. Like coves they normally run along the entire length of a wall, however, they are located a foot or two below the ceiling and open both at the top and at the bottom (top section of Figure 8.30). This means that they are able to reflect light both from the ceiling and the upper part of the wall. While the resultant light distribution is still quite diffuse, the reflecting surfaces extend from the ceiling to the upper portions of the wall(s) thereby accentuating to a greater degree than coves the three-dimensional character of the room.

Cornices are formed by moving a valence board directly to the ceiling as shown in the mid-section of Figure 8.30. As a result, reflected light is received only from the upper portions of the wall(s). With the ceiling more or less in darkness cornice lighting can produce an intimate environment that might be suitable for a restaurant or, in combination with direct-indirect luminaires, for a lounge or waiting area (e.g., health facility).

Luminous Wall Panels are sometimes used in windowless spaces to provide an impression of window light (bottom section of Figure 8.30). Care must be taken to avoid glare conditions by keeping the brightness of the wall panel low. This is particularly important because a luminous wall panel is in the direct line of sight of the occupants of the space.

8.5 The Lumen Method of Lighting Design

The Lumen Method of artificial lighting design provides a means of calculating the average illumination on a horizontal plane over the whole interior from a known lighting installation or, alternatively, the number and wattage of lamps required to provide a specified level of average illumination. In either case, the direct and reflected components of light are taken into account for the particular room dimensions, reflectance, and type of luminaire. Calculations are very much simplified by the use of tables, and the method is in general applied to lighting installations employing approximately, symmetrically disposed overhead lighting units.

The advantages of the method are its simplicity, broad applicability to rectangular rooms, and ability to provide a quick ballpark estimate of the lighting requirements during the early stages of the design process. Its overall disadvantage is that it over-simplifies lighting design by assuming a rectangular room, a uniform distribution of luminaires and surface reflectances, by not considering obstructions or furniture that might block light, and by ignoring the specific directional properties of luminaires that might be important for certain tasks and/or lighting themes. In summary, while the Lumen Method may serve as a convenient tool for the approximate sizing of lighting installation during the early design stages, it should not be considered as an alternative to the detailed lighting design analysis that should take place at the later design stages. However, having used the Lumen Method during the earlier design stage will reduce the risk of having to make major design changes during the more detailed analysis at a later stage.

Fundamental to the Lumen Method of design is the concept of Coefficient of Utilization (CU), which is defined as:

CU = [total flux on work plane (F_P)] / [total flux emitted by lamps (F_L)] ………. (8.2)

Normally, only a portion of the flux emitted by the lamps reaches the work plane and therefore the Coefficient of Utilization is always less than unity. Light flux is lost by obstructions and absorption due to walls and ceiling. The numerical value of the Coefficient of Utilization for any particular lighting installation will depend on the following factors (Figure 8.31):

- ***Type and efficiency of the luminaire:*** The more light flux that is directed to the work plane the higher the value of the Coefficient of Utilization.
- ***Reflectivity of room surfaces:*** The reflectivity of finishes is expressed in terms of a percentage reflection factor.
- ***Mounting height of luminaire:*** The proportion of flux absorbed by the walls will depend mostly on the mounting height and the room dimensions. Increases in mounting height will tend to decrease the coefficient of utilization.

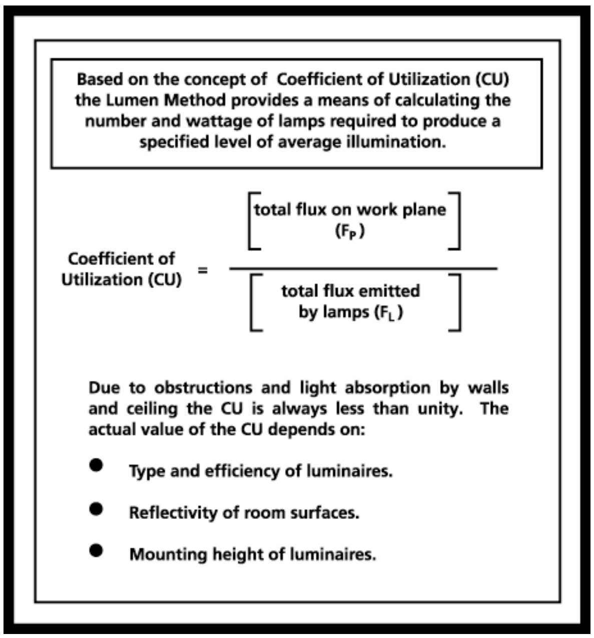


Figure 8.31: Coefficient of Utilization (CU)

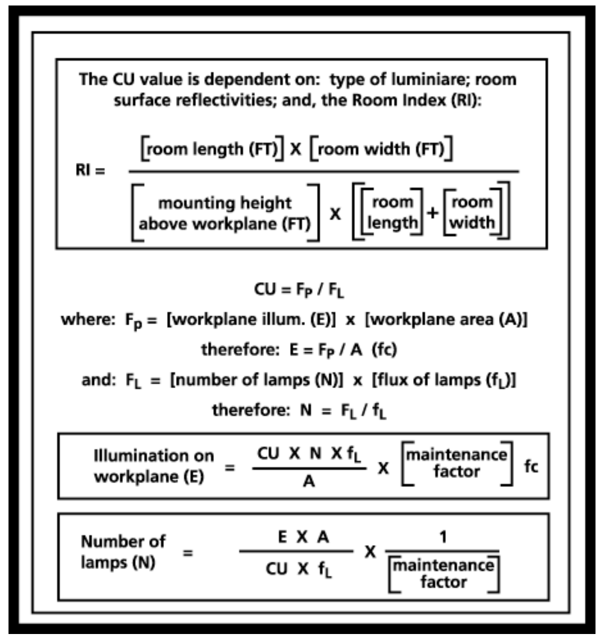


Figure 8.32: Room Index (RI)

Tables of Coefficients of Utilization (CU) normally take into account the type of luminaire, the reflectivity of the room surfaces, the mounting height, and the room dimensions. Both mounting height (H FT) and room proportions (i.e., room length (L FT) and room width (W FT)) are embraced by the concept of Room Index (RI), in the following manner (Figure 8.32):

$$\mathbf{RI} = \frac{\mathbf{[room\ length]\ x\ [room\ width]}}{\mathbf{[mounting\ height\ above\ work\ plane]\ x\ [room\ length + room\ width]}} \quad \ldots\ldots\ (8.3)$$

Having obtained the Room Index, the Coefficient of Utilization is obtained from tables (such as Table 8.1) for the appropriate type of luminaire and room surface reflection factors. To look up the Coefficient of Utilization in Table 8.1 we find the appropriate luminaire with the closest Light Output Ratio (LOR) in the left column. The corresponding CU value is given by the correct combination of the Room Index value and the ceiling and wall reflectances.

The numerical value of the Coefficient of Utilization is then applied as follows:

CU = [total flux on work plane (F_P)] / [total flux emitted by lamps (F_L)] .... (8.2)

F_P = [illumination on work plane (E)] x [area of work plane (A)] .... (8.4)

$$F_L = [\text{number of lamps } (N)] \times [\text{flux emitted by one lamp } (F_L)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8.5)$$

Table 8.1: Typical Coefficient of Utilization Table

Description of Fitting, and Typical Downward Light Output Ratio (%)	**Basic Downward LOR (%)**	**Reflection Factor (%)**							
		Ceiling	70		50		30		0
		Walls	50	10	50	10	50	10	0
		Room Index	**Coefficient of Utilization**						
250 W. Reflectorized mercury lamp (100). (fitting for color-corrected mercury lamp)	100	0.6	.54	.44	.53	.44	.52	.44	.43
		0.8	.65	.55	.64	.55	.63	.55	.54
		1.0	.71	.60	.70	.60	.68	.60	.59
		1.25	.77	.64	.76	.66	.76	.66	.65
		1.5	.82	.72	.81	.71	.80	.71	.70
		2.0	.90	.80	.87	.79	.86	.78	.76
		2.5	.93	.84	.90	.83	.90	.82	.80
		3.0	.96	.88	.93	.87	.92	.85	.83
		4.0	.98	.92	.96	.91	.94	.89	.87
		5.0	1.00	.96	.99	.94	.96	.92	.90
Enamel Slotted trough, louvred (45-55) Shallow ceiling-mounted louvre panel (40-50)... Louvred recessed (module) fitting (40-50)... (fittings for fluorescent lamps)	50	0.6	.27	.22	.26	.22	.26	.22	.20
		0.8	.32	.27	.32	.27	.31	.27	.25
		1.0	.35	.30	.35	.30	.34	.30	.29
		1.25	.38	.32	.38	.33	.38	.33	.32
		1.5	.41	.36	.40	.35	.40	.35	.34
		2.0	.45	.40	.43	.39	.43	.39	.38
		2.5	.47	.42	.45	.41	.45	.41	.40
		3.0	.48	.44	.46	.43	.46	.42	.41
		4.0	.49	.46	.48	.45	.47	.44	.43
		5.0	.50	.48	.49	.47	.48	.46	.45
Suspended pan-shaped fitting, partly open top, louvred beneath (50) ... (fitting for fluorescent lamp)	50	0.6	.32	.24	.30	.24	.29	.23	.21
		0.8	.39	.31	.36	.29	.35	.29	.27
		1.0	.43	.35	.40	.34	.38	.32	.30
		1.25	.47	.39	.44	.38	.42	.35	.32
		1.5	.51	.43	.47	.41	.44	.38	.35
		2.0	.56	.49	.51	.46	.47	.42	.38
		2.5	.58	.52	.53	.49	.49	.44	.40
		3.0	.60	.55	.55	.51	.51	.46	.41
		4.0	.63	.58	.57	.54	.52	.48	.43
		5.0	.64	.60	.59	.56	.53	.50	.45
Open-end enamel trough (75-85) ... Closed-end enamel trough (56-83) ... Standard dispersive IndustrialReflector (77) (fitting for filament or fluorescent lamps)		0.6	.36	.28	.35	.28	.35	.28	.27
		0.8	.45	.37	.44	.37	.44	.37	.36
		1.0	.49	.40	.49	.40	.48	.40	.39
		1.25	.55	.46	.53	.45	.52	.45	.43
		1.5	.58	.49	.57	.49	.55	.49	.48
		2.0	.64	.55	.61	.55	.60	.54	.52
		2.5	.68	.60	.65	.59	.64	.58	.56
		3.0	.70	.62	.67	.61	.65	.61	.59
		4.0	.73	.67	.70	.65	.67	.64	.62
		5.0	.75	.69	.73	.67	.70	.67	.65

Combining equations 8.2, 8.4, and 8.5 and incorporating a maintenance factor (M), we obtain:

$$E \;=\; [CU \times N \times F_L \times M] \,/\, A \quad (\text{lm/SF or fc}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8.6)$$

Alternatively, if the illumination on the work plane (E) is specified, equation (8.6) may be rewritten in terms of the number of lamps (N) required, as follows:

$$N \;=\; [E \times A] \,/\, [CU \times F_L \times M] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8.7)$$

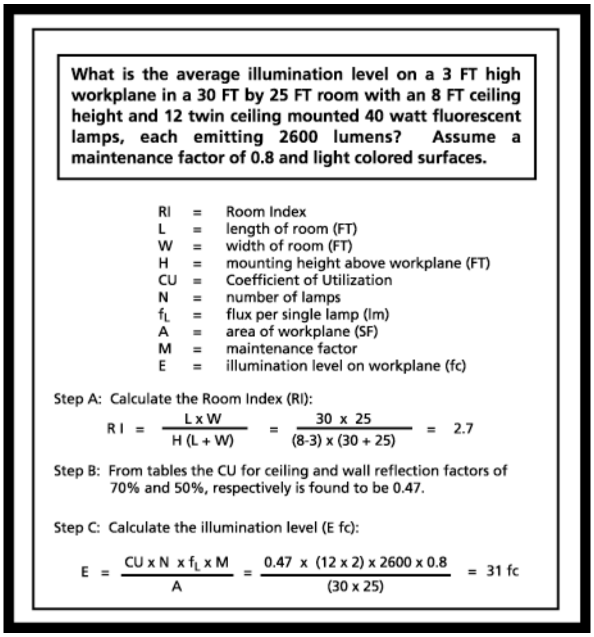


Figure 8.33: Calculation of the average illumination level (E lm/SF or fc)

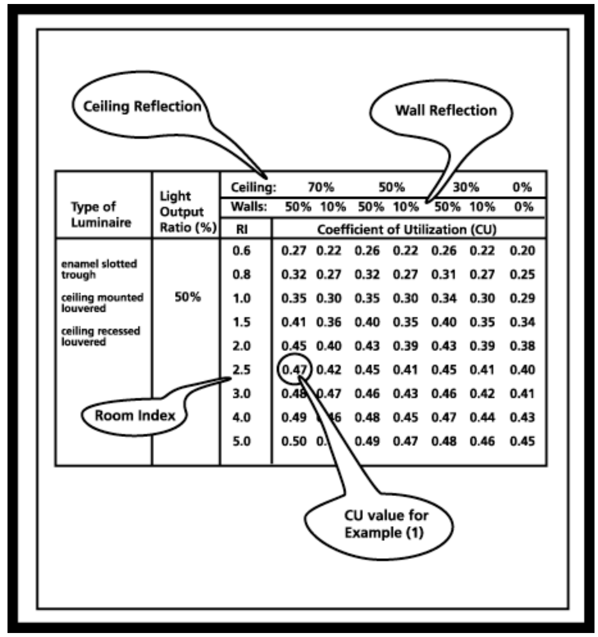


Figure 8.34: Looking up the CU value for the example shown in Figure 8.33

An example of the application of equation (8.6) is shown in Figure 8.33. As a second example we will calculate the average illumination level on a 3FT high work plane, which would be obtained from 24 twin 40W fluorescent lamps each emitting 2600 lm of light flux and ceiling mounted in 24 louvered luminaires. The room has dimensions 60FT long (L), 25FT wide (W) and 9FT high (H) with light colored walls and ceiling. We will assume a maintenance factor (M) of 0.8.

Step 1: Calculate the Room Index (RI) according to equation (8.3):

$$\mathbf{RI = L \times W \;/\; H\,(L + W)}$$

$$RI = [60 \times 25] \;/\; [(9 - 3) \times (60 + 25)] = 3 \text{ (approx.)}$$

Step 2: Find the coefficient of utilization (CU) from Table 8.1, if the reflection factors for the ceiling and walls are 70% and 30%, respectively.

$$CU = 0.45 \text{ (approx.)}$$

Step 3: Calculate the average illumination level on the work plane (E) if the flux per single lamp is 2600 lm and the maintenance factor (M) is 0.8, using equation (8.6):

$$\mathbf{E = [CU \times N \times F_L \times M] \;/\; A \quad (lm/SF\ or\ fc)}$$

$$E = [0.45 \times (24 \times 2) \times 2600 \times 0.8] \,/\, (60 \times 25) \;\; \text{lm/SF or fc}$$

$$E = 30 \text{ lm/SF or fc}$$

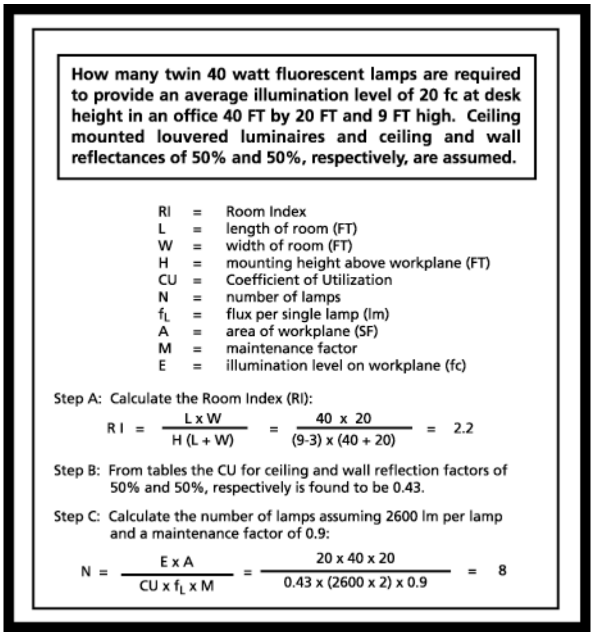


Figure 8.35: Number of lamps required for a given illumination level

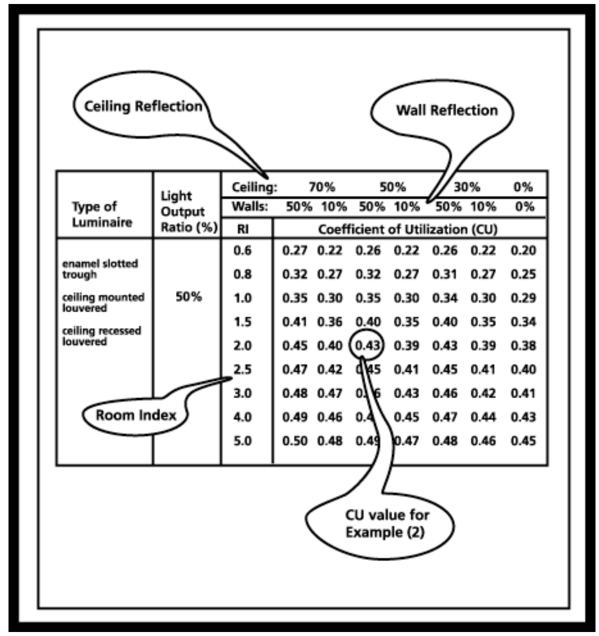


Figure 8.36: Looking up the CU value for the example shown in Figure 8.35

Two separate examples of the reverse calculation are shown in Figures 8.35 and 8.36, and below. In the case of the example (below) we will determine the number of triple 40W tubular fluorescent lamps required to provide an average illumination (E) of 25 fc at desk level in an architectural drawing office 40FT long (L), 20FT wide (W) and 10FT high (H). A suspended pan-shaped fitting, partly open top and louvered beneath, will be used. Assume the reflection factor of the ceiling to be 50% and 10% for the walls. The light flux produced by a single lamp is 2600 lm and the maintenance factor (M) is 0.85.

Step 1: Calculate the Room Index (RI) according to equation (8.3):

RI = L x W / H (L + W)

RI = [40 x 20] / [(10 - 3) x (40 + 20)] = 1.9 (approx.)

Step 2: Find the coefficient of utilization (CU) in Table 8.1 if the reflection factors for the ceiling and walls are 50% and 10%, respectively.

CU = 0.46 (approx.)

Step 3: Given that the flux (E) per single lamp is 2600 lm and incorporating a maintenance factor (M) of 0.85, find the number of triple 40W units required. Apply equation (8.7):

N = [E x A] / [CU x F_L x M]

N = [25 x (40 x 20) / [0.46 x 2600 x 0.85]

N = 20 single lamps (or 7 triple 40W units)

8.6 The Room Cavity Ratio

Some state and national building energy standards, such as California Title 24, utilize the concept of Room Cavity Ratio (RCR) as a metric for determining the allowable artificial lighting load in building spaces. Typically, a floor plan is divided into *areas*, then the RCR is calculated for each *area*, and finally either the maximum allowable wattage per square foot (W/SF) or illumination level in lumen per square foot (lm/SF) or footcandles (fc) is provided by a table.

An *area* is normally defined in terms of its perimeter enclosure. For example, any space with 75% or more of its perimeter defined by either solid or transparent floor-to-ceiling partitions or walls. The RCR of such an *area* is then calculated with the following equation (8.8):

$$\mathbf{RCR} = \frac{\mathbf{5\ [light\ fixture\ height\ above\ task\ surface]\ x\ [area\ length + area\ width]}}{\mathbf{[area\ length]\ x\ [area\ width]}} \quad \mathbf{\ldots\ (8.8)}$$

Maximum wattage (or illumination) allowances will be higher for larger RCR values. For example, the allowable wattage for the spray booth *area* of an aircraft manufacturing plant may be 2.4 W/SF if the RCR is less or equal to 5 and 3.4 W/SF if the RCR is greater than 5.

8.7 The PSALI Concept

The Permanent Supplementary Artificial Lighting of Interiors (PSALI) concept was developed in England in the 1950s for the purpose of supplementing daylight with artificial light in those building spaces where the daylight level is inadequate. Particularly, in the case of multi-story buildings there is a tendency for ceiling heights to be low and rooms to be deep, so that the maximum number of floors can be accommodated within a minimum building height. Moreover, large windows are likely to lead to conditions of sky-glare and excessive heat transfer.

At the time, and this was well before energy became scarce and prohibitively expensive, it was argued on purely economic grounds that there were benefits to be found in deleting windows altogether. However, even though a number of fairly successful windowless buildings were built, the counterargument that windows are a significant factor in contributing to the physical and psychological well-being of the building occupants generally prevailed.

The underlying research into the optimum means of integrating natural and artificial light was conducted by the British Research Establishment. One of the basic assumptions of the PSALI concept that grew out of this research is the notion that daylight should remain the dominant feature of a building interior unless the particular occupancy specifically requires the exclusion of daylight (e.g., some museums and certain medical facilities). Accordingly, PSALI systems are designed on the principle that artificial lighting should provide adequate illumination levels where natural light is inadequate and mitigate the appearance of gloom in those parts of a building space that are remote from external windows. As a rule of thumb the artificial lighting level (E_{PSALI}) that is required in support of a PSALI installation may be related to the average value of the Daylight Factor ($DF_{average}$) in the room under consideration, as follows[3]:

$$\mathbf{E_{PSALI} = [\pi\ x\ DF_{average}\ x\ (external\ illumination\ level)]\ /\ 10\quad (lm/SF\ or\ fc)\ \ldots\ldots\ (8.9)}$$

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[3] In the original form of equation (8.9) the PSALI illumination level is calculated as a function of the *sky luminance* (measured in foot lamberts (fL) or candela/SF) and not the *external illumination level* as shown above. However, for a luminous hemisphere the illumination level at the center of the hemisphere is numerically equal to the luminance of the hemisphere.

It is suggested that the section of the room where this PSALI lighting is required may be confined to the area where the Daylight Factor is 20% or less of that near the window. Unfortunately, the above relationship cannot be applied universally. In regions where clear skies are predominant the sky luminance will differ markedly with orientation, while the overall luminance range is normally very wide. For example, the range between an overcast and bright sky in England is about 500 fL to 4000 fL, while in parts of California the range is likely to extend from 800 fL to 8000 fL. It is therefore apparent that PSALI installations will tend to be very expensive in terms of energy usage and therefore uneconomical in regions where bright skies are a normal occurrence.

Light fittings for PSALI installations are very often of the laylight[4] type, louvered to avoid glare and some 4FT wide running along the length of the room with the back edge about 3FT from the inner wall. It has been suggested that the luminance of such laylights should not exceed 200 fL, to avoid discomfort glare conditions.

Since the artificial illumination level of a PSALI installation will invariably be higher during the day than at night, it follows that the level of lighting should be reduced as the daylight fades. This may be achieved by either providing two separate installations or by providing means of switching out a percentage of the total light sources as necessary. It is also important to consider the color rendition properties of the artificial light sources. The PSALI installation should provide light near to the color of daylight, while the night light should preferably be of a warmer color. In fact, it is generally recognized that the lower the level of illumination the warmer the color of the artificial light source should be.

8.8 Lighting Power Budgets

The concept of limiting the consumption of electric power by mandating compliance with standards that assign power budgets to spaces in buildings based on functional activity gained a great deal of momentum with the emergence of an energy crisis in the 1970s. At that time such standards were incorporated in new energy codes that are enforced by local government agencies responsible for ensuring compliance with building codes.

The determination of the Lighting Power Budget of a building according to the procedure recommended by the American National Standards Institute[5] involves determination of the separate power budgets of:

(a) Building interior spaces that are heated and/or cooled.
(b) Covered walkways, open roofed areas, porches, and similar spaces where lighting is required.
(c) Building exteriors, including entrances, exits, parking areas, driveways, and outdoor storage and activity areas.

Building Interior: The lighting power budget of a room is the total electric power (watts) that will be available for use in that room for lighting. It is calculated as the product of a base Unit Power Density (UPD) allocated by building codes to the kind of activities the room is designed to support,

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4 A laylight may be described as a large area light source recessed into the ceiling.

5 Energy Conservation in New Buildings, ANSI/ASHRAE/IES 90A-1980, American National Standards Institute, New York. Energy Management Committee of the IES: IES Recommended Lighting Power Budget Determination Procedure – EMS-1, Illuminating Engineering Society, New York, September 1978.

a Room Factor (RF) based on the size of the room, and a Space Utilization Factor (SUF) that accounts for the ratio of the workstation area to the total floor area of the room. More specifically:

> The Unit Power Density (UPD) in watts/SF is available in tables and takes into account the relative sizes of the tasks, workstations, and non-critical areas in the room, the illuminance in each of those areas, and the efficiency of the light sources.
>
> The Room Factor (RF) ranges from 1.00 to 2.00 and is based on the length, width and ceiling height dimensions of the room.
>
> The Space Utilization Factor (SUF) ranges from 0.4 to 1.0 and represents the ratio of the total workstation area ($A_{Workstn}$) to the area of the room (A_{Room}), as follows:
>
> $A_{Workstn} / A_{Room} > 0.5$ ……………. SUF = 1.00
> $A_{Workstn} / A_{Room} = 0.5$ ……………. SUF = 1.00
> $A_{Workstn} / A_{Room} < 0.5$ ……………. SUF = 0.85
> $A_{Workstn} / A_{Room} < 0.4$ ……………. SUF = 0.70
> $A_{Workstn} / A_{Room} < 0.3$ ……………. SUF = 0.55
> $A_{Workstn} / A_{Room} < 0.2$ ……………. SUF = 0.40
>
> A workstation area (i.e., task area) is assumed to be 50 SF. In the relatively rare cases where a task area exceeds 50 SF the workstation area becomes the actual task area.

room budget = A_{Room} x UPD x RF x SUF watts ………………….. (8.10)

The total building interior power budget will be the summation of the individual room budgets plus an allowance of 0.2 watts/SF for unlisted spaces (i.e., the difference between the gross building floor area and the total room area multiplied by 0.2).

Building Exterior: Supplementary and façade lighting (5% of the total Building Interior power budget).

Project/Site: Roofed entrances (4.0 to 10.0 watts/SF depending on building type), entrances without canopies (30.0 watts/SF), exits (20.0 watts per linear foot (watts/LF)), loading areas (0.3 watts/LF), loading doors (20.0 watts/LF), outdoor storage (0.2 watts/LF), private parking lots (20.0 watts/LF), public parking lots (30.0 watts/LF), private driveways (2.0 watts/LF), and public driveways (3.0 watts/LF).

> Example: For a small community center (building type) with a building floor area of 2,258 SF the lighting power budget calculations might produce the following results:

Room Type	Room Area	Room Factor	Workstations Number	Workstations Area	Space Utilization Factor (SUF)	Base UPD	Power Budget
Entrance	320 SF	1.30	0	0 SF	1.00	1.0	416 watts
Office-1	150 SF	1.45	1	50 SF	0.70	2.2	335 watts
Kitchenette	150 SF	1.45	0	0 sf	1.00	1.7	370 watts
Office-2	150 SF	1.45	1	50 SF	0.70	2.2	335 watts
Library	1125 SF	1.07	2	100 SF	0.40	2.2	1064 watts
Restroom-1	80 SF	1.75	0	0 SF	1.00	0.7	98 watts
Restroom-2	100 SF	1.00	0	0 SF	1.00	0.7	70 watts
Storeroom	70 SF	1.80	0	0 SF	1.00	0.7	88 watts
Corridor	60 SF	1.85	0	0 SF	1.00	0.6	67 watts
	2,205 SF						2,843 watts

Difference between the sum of the listed room areas and the building floor area is 53 SF (2,258 -2,205 = 53).

allowance for unlisted floor area (53 SF) @ 0.2 watts/SF =	11 watts
façade lighting: 5% of building internal load (2843 watts) =	142 watts
	153 watts
1 roofed entrance (80 SF) @ 6.0 watts/SF =	480 watts
1 exit (5 FT) @ 20.0 watts/LF =	100 watts
outdoor storage (10 FT) @ 0.2 watts/LF =	2 watts
2 private parking spaces (18 FT) @ 20.0 watts/LF =	360 watt
18 public parking spaces (162 FT) @ 30.0 watts/LF =	4860 watts
Private driveway (40 FT) @ 2.0 watts/LF =	80 watts
	5,882 watts

Building Internal =	2,843 watts	(1.26 watts/SF)
Building External =	153 watts	(0.07 watts/SF)
Project/Site =	5,882 watts	(2.60 watts/SF)
Total electric lighting load =	**8,878 watts**	(3.93 watts/SF)

8.9 Questions Relating to Chapter 8

Answers to the following multiple-choice questions with references to the appropriate text (by page number) may be found at the back of the book.

1. **In reference to the radiant energy emitted by a black body at different temperatures, it is apparent that the *ideal artificial light source* would need to operate at a color temperature of about:**

   A. 2,000 ˚ K
   B. 3,000 ˚ K
   C. 4,000 ˚ K
   D. 5,000 ˚ K
   E. 6,000 ˚ K

2. **Although the incandescent or filament lamp has the advantages of simplicity of manufacture and comparatively good color rendition, it cannot be considered an efficient light source since only about X% of the emitted energy is in the visible range.**

   A. X = 30%
   B. X = 20%
   C. X = 7%
   D. X = 90% because the above statement is incorrect and the filament lamp is quite an efficient light source.
   E. X = 35%

3. **Which of the following light-producing processes is of immediate, practical importance in the artificial lighting of office buildings.**

   A. Incandescence.
   B. Electric discharge in gas or vapor.
   C. Electroluminescence.
   D. Fluorescence.
   E. All of the above (i.e., A, B, C, and D) are equally important.

4. **Which of the following properties of an artificial light source would you consider to be most important for the lighting installation of an *Art Gallery*:**

   A. High luminous efficiency.
   B. Appropriate color rendition.
   C. Silent operation and low heat output.
   D. Long useful life.
   E. Good lumen maintenance.

5. **Tungsten is normally chosen for the *filament* material of an incandescent lamp because:**

   A. It is a relatively inexpensive material.
   B. It has a high melting point and slow rate of evaporation.
   C. It is one of the few materials that can be raised to incandescence by the passage of an electric current.
   D. It produces radiation that lies mainly in the infra-red region.
   E. None of the above statement (i.e., A, B, C, and D) are correct.

6. **The function of the gas contained in the bulb of an incandescent lamp is mainly to:**

   A. Increase the rate of evaporation of the filament.
   B. Improve the color rendition of the lamp.
   C. Increase the life of the filament.
   D. Stop the lamp from overheating.
   E. None of the above statements (i.e., A, B, C, and D) are correct.

7. **The color rendition of filament lamps is commonly accepted as being pleasant and flattering to the complexion. Which (if any) of the following statements is not correct:**

   A. Filament lamps will tend to soften the appearance of colored surfaces.
   B. Most colors when viewed under the light from a filament lamp will tend to have a red-brown tint.

C. The light from a filament lamp has a spectral distribution that is very similar to daylight.

D. The light from a filament lamp has a spectral distribution that is not similar to a sodium vapor lamp.

E. All of the above statements (i.e., A, B, C, and D) are correct.

8. **In all discharge lamps light is produced by the passage of an electric current through a *gas or vapor*. It is the function of the gas to:**

   A. Convert ultra-violet radiation into light.

   B. Ensure that the lamp does not overheat.

   C. Facilitate initiation of the discharge.

   D. Prolong the useful life of the lamp.

   E. None of the above statements (i.e., A, B, C, and D) are correct.

9. **Which of the following components (if any) does *not* belong to a discharge lamp:**

   A. A filament.

   B. An arc tube.

   C. Two electrodes.

   D. A choke circuit.

   E. All of the above (i.e., A, B, C, and D) are components of a typical discharge lamp.

10. **The most limiting feature of the low-pressure sodium lamp is:**

    A. Its unique yellow radiation.

    B. Its unique infra-red radiation.

    C. Its life expectancy.

    D. Its luminous efficiency.

    E. Its lumen maintenance.

11. **Which of the following statements (if any) does *not* relate to fluorescent lamps:**

    A. Although the color rendition properties of the fluorescent lamp can be partly controlled, it is not possible to exactly reproduce daylight with this lamp.

    B. Electrical circuits for fluorescent lamps are normally designed to limit the voltage and provide a high starting current initially.

    C. The light output of a fluorescent lamp will vary with the surface temperature of the tube. A fall-off in light will occur in excessively hot or cold temperatures.

    D. All of the above statements (i.e., A, B and C) relate to fluorescent lamps.

E. Two of the above statements (i.e., A, B and C) do not relate to fluorescent lamps.

12. **Which of the following statements (if any) are *not* correct:**

    1. **The expected life span of a filament lamp is about 1/7th that of a fluorescent lamp.**
    2. **Fluorescent lamps are available in a very limited wattage range.**
    3. **The color rendition of a mercury vapor lamp is very poor in the uncorrected form, but a little better in the color corrected form.**
    4. **The luminous efficiency of a sodium vapor lamp is about five times as high as that of an incandescent lamp.**
    5. **Fluorescent lamps require a current limiting device in the form of a resistance or impedance.**
    6. **The fluorescent lamp produces soft and diffuse shadows, although its brightness is sufficiently high to cause glare if not screened.**

    Select the correct solution for this question from the following:

    A. Statements 1, 2, 3, 4, 5 and 6 are correct.
    B. Statements 1, 2, 3, 4, 5 and 6 are incorrect.
    C. Statements 1, 3 and 4 are incorrect.
    D. Statements 1, 3, 4 and 6 are incorrect.
    E. Statement 4 is incorrect.

13. **While for most industrial installations (i.e., luminaires) it will be possible to provide adequate shielding by means of metal troughs, in the case of fluorescent units containing more than one tube louvers are used for the following reasons:**

    A. For the sake of better appearance.
    B. To diffuse the light.
    C. To improve the color rendition of the lamp.
    D. To decrease the depth of the trough.
    E. None of the above statements (i.e., A, B, C, and D) are correct.

14. **Which of the following lighting systems (if any) would you recommend to be placed over a circular conference table in an architectural office in the absence of any background light source.**

    A. Direct
    B. Semi-Direct
    C. Direct-Indirect
    D. Indirect
    E. None of the above (i.e., A, B, C, and D) are suitable for this application.

15. **Which (if any) of the following applications is suitable for mercury vapor lamps (i.e., in the color corrected form):**

    A. high bay factory lighting
    B. street lighting
    C. general external lighting
    D. All of the above statements (i.e., A, B and C) are suitable applications.
    E. None of the above statements (i.e., A, B and C) are correct.

16. **Which of the following light sources is *most efficient* (i.e., has the highest luminous efficiency):**

    A. incandescent lamp (argon filled)
    B. metal halide lamp
    C. tungsten-halogen lamp
    D. “Cool white” fluorescent lamp
    E. “Cool Deluxe” fluorescent lamp