

Light Sources

6

A BRIEF HISTORY OF LIGHT SOURCES^{1,2,3}

The earliest man-made light sources were fire, torches, and candles. Ancient Egyptians used hollowed-out stones filled with fat, with plant fibers as wicks. These were the first candles, and they date back to about 3000 BC. In the Middle Ages, candles were made of tallow, a type of animal fat; later they were made of beeswax or paraffin. Modern candles can still be thought of as a type of fat lamp, but their use today is almost entirely decorative.

Ancient Greeks and Romans made lamps from bronze or pottery that burned olive oil or other vegetable oils in their spouts. Many oil lamps appeared during the Middle Ages, when reflectors were added to their designs. Early American colonists used fish oil and whale oil in their Betty lamps. Many improvements were made in the design and fabrication of these lamps over the years, but none produced light efficiently until 1784, when a Swiss chemist named Argand invented a lamp that used a hollow wick to allow air to reach the flame, resulting in a bright light. Later, a glass cylinder was added to the Argand lamp allowing the flame to burn better. With the birth of the petroleum industry, kerosene became a widely used fuel in these lamps.

In the 1800s gas lamps became popular as street lights, originating in London, England. The gas lamp had no wick, but its chief drawback was an open flame that produced considerable flicker. The electric lamp replaced gas lamps in the late 1800s and early 1900s. The first electric lamp was the carbon-arc lamp, demonstrated in 1801 by Sir Humphrey Davy, but electric lights became popular only after the incandescent lamp was developed independently by Sir Joseph Swan in England and Thomas Edison in the United States. The latter patented his invention in 1879 and subsequently made the invention the commercial success that it is today. Figure 6-1 illustrates the history of different light sources.

This century has seen a huge increase in the number of available light sources in the marketplace, starting with improvements in the Edison lamp, then the introduction of mercury vapor lamps in the 1930s, followed closely by fluorescent lamps at the 1939 World Fair. Tungsten-halogen lamps were introduced in the 1950s; metal halide and high pressure sodium (HPS) lamps in the 1960s. The introduction of electrodeless lamps in the 1990s is an indication that the industry is dynamic, and the introduction of new light sources is expected to continue at least at the present rate well into the next century. Figure 6-2 lists the approximate luminance of various light sources.

This chapter describes the various light sources and control equipment now available. Fundamental information concerning the generation of light and the operating principles of electric light sources is given in Chapter 1, Light and Optics, and in other references.¹ The sun and sky as light sources are covered in Chapter 8, Daylighting. For techniques on the measurement of light and light output from light sources, see Chapter 2, Measurement of Light and Other Radiant Energy. Some specialty lamps are discussed in Chapter 15, Theater, Television, and Photographic Lighting, and data on UV radiation from some common sources are found in the museum section in Chapter 14, Lighting for Public Places and Institutions.

With such a wide selection of light sources on the market, it is likely that several different choices could be made for a given lighting application. While the general characteristics can be provided, a definitive list with absolute values for all types and manufacturers would be too extensive for this chapter. Figure 6-3 provides a comparison of significant performance characteristics of commonly used lamps. Explanation of the parameters will be provided later in this chapter.

Figure 6-4 shows shapes of commonly available lamps. Each lamp shape also includes the corresponding American National Standards Institute (ANSI) designation used by many lamp manufacturers in their catalogs. The designation is typically followed by a number, which expresses the diameter of the lamp in multiples of 1/8 inch, so that T-12 refers to a tubular fluorescent lamp with a diameter of 12/8 or 1.5 in. (38 mm), and PAR 30 is a parabolic reflector lamp with a diameter of 30/8 or 3.75 in. (95 mm). Manufacturers use a variety of bases, discussed in the individual lamp sections below.

Light sources, luminaires, controls, and system layout are closely interrelated. A light source that is appropriate for one type of application may be impractical for another. See the application chapters that follow for guidance on light source selection.

INCANDESCENT FILAMENT AND TUNGSTEN-HALOGEN LAMPS

The primary consideration of filament lamp design is that it will produce the spectral radiation desired (visible, infrared, ultraviolet) most economically for the application intended. Realization of this objective in an incandescent filament lamp requires the specification of the following: filament material, length, diameter, form, coil spacing, and mandrel

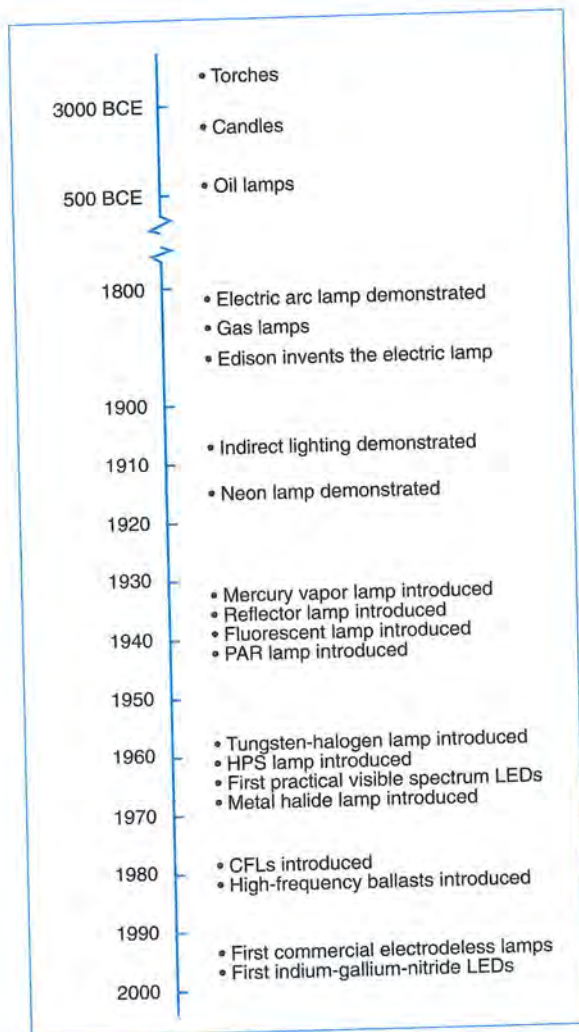


Figure 6-1. Time line of light sources.

size (the mandrel is the form on which the filament is wound); lead-in wires; number of filament supports; filament mounting method; vacuum or filling gas; gas pressure; gas composition; and bulb size, shape, glass composition, and finish. The manufacture of high-quality lamps requires adherence to these specifications and necessitates careful process controls.

The construction and principle of operation of incandescent filament and tungsten-halogen lamps are similar; however, the halogen regenerative cycle enables a tungsten-halogen lamp to provide the following benefits compared to a conventional incandescent lamp: longer life, higher color temperature, higher efficacy, and no bulb blackening.

Incandescent Lamp Construction

Filaments. The efficacy of light production depends on the temperature of the filament. The higher the temperature of

the filament, the greater the portion of the radiated energy that falls in the visible region. For this reason it is important in the design of a lamp to keep the filament temperature as high as is consistent with satisfactory life. For example, iron is not a good filament material because it melts at a relatively low temperature (1527°C) for efficient light production. Numerous materials have been tested for filament suitability. Desirable properties of filament materials are a high melting point, low vapor pressure, high strength, high ductility, and suitable radiating characteristics and electrical resistance.

Tungsten for Filaments. Early incandescent lamps used carbon, osmium, and tantalum filaments, but tungsten has many desirable properties for use as an incandescent light source. Its low vapor pressure and high melting point, 3382°C (6120°F), permit high operating temperatures and consequently high efficacies. Drawn tungsten wire has high strength and ductility, allowing the uniformity necessary for present-day lamps. Alloys of tungsten with other metals such as rhenium are useful in some lamp designs. Thoriated tungsten wire is used in filaments for rough service applications.

Radiating Characteristics of Tungsten.⁴⁻⁷ The ratio of the radiant exitance of a thermal radiator to that of a blackbody radiator is called the emissivity, and thus the emissivity of a blackbody is 1.0 for all wavelengths (see Chapter 1, Light and Optics). Tungsten is a selective radiator because its emissivity is a function of the wavelength. Figure 6-5 illustrates the radiation characteristics of tungsten and of a blackbody and shows that for the same amount of visible radiation, tungsten radiates only a percentage of the total radiation from a blackbody at the same temperature. (The intensity of curve B is approximately 76% of curve A.)

Only a small percentage of the total radiation from an incandescent source is in the visible region of the spectrum. As the temperature of a tungsten filament is raised, the radiation in the visible region increases (Figure 6-6), and thus the luminous efficacy increases. The luminous efficacy of an uncoiled tungsten wire at its melting point is approximately 53 lm/W. In order to obtain long life, it is necessary to operate a filament at a temperature well below the melting point, resulting in a loss in efficacy.

Resistance Characteristics of Tungsten. Tungsten has a positive resistance characteristic, so that its resistance at operating temperature is much greater than its cold resistance. In general-service lamps, the hot resistance is 12 to 16 times the cold resistance. Figure 6-7 illustrates the change in resistance of the tungsten filament with temperature for various lamps. The low cold resistance of tungsten filaments results in an initial in-rush of current that, because of the reactive impedance characteristic of the circuit, does not reach the theoretical value indicated by the ratio of the hot-to-cold resistance. Figure 6-8 gives the effect of the change in resistance on the current in incandescent filament lamps. The in-rush current due to incandescent filament loads is important

Figure 6-2. Approximate Luminance of Various Light Sources

Light Source		Approximate Average Luminance (cd/m ²)
Natural light sources		
Sun (at its surface)	—	2.3×10^9
Sun (as observed from earth's surface)	At meridian	1.6×10^9
Sun (as observed from earth's surface)	Near horizon	6×10^6
Moon (as observed from earth's surface)	Bright spot	2.5×10^3
Clear sky	Average brightness	8×10^3
Overcast sky	—	2×10^3
Lightning flash	—	8×10^{10}
Combustion sources		
Candle flame (sperm)	Bright spot	1×10^4
Kerosene flame (flat wick)	Bright spot	1.2×10^4
Illuminating gas flame	Fish-tail burner	4×10^3
Welsbach mantle	Bright spot	6.2×10^4
Acetylene flame	Mees burner	1.1×10^5
Photoflash	—	1.6×10^8 to 4×10^8 peak
Nuclear sources		
Atomic fusion bomb	0.1 msec after firing—30-m dia. ball	2×10^{12}
Self-luminous paints	—	0.2 to 0.3
Incandescent lamps		
Carbon filament	3.15 lm/W	5.2×10^5
Tantalum filament	6.30 lm/W	7×10^5
Tungsten filament	Vacuum lamp 10 lm/W	2×10^6
Tungsten filament	Gas-filled lamp 20 lm/W	1.2×10^7
Tungsten filament	750-W projection lamp 26 lm/W	2.4×10^7
Tungsten filament	1200-W projection lamp 31.5 lm/W	3.3×10^7
RF (radio frequency)	24-mm diameter disk	6.2×10^7
Blackbody at 6500 K	—	3×10^9
Blackbody at 4000 K	—	2.5×10^8
Blackbody at 2042 K	—	6×10^5
60-W inside frosted	—	1.2×10^5
10-W inside frosted	—	2×10^4
Tungsten-halogen sources		
3000 K CCT	—	1.3×10^7
3200 K CCT	—	2.3×10^7
3400 K CCT	—	3.9×10^7
Fluorescent sources		
CFL	36-W twin tube	3×10^4
T-5	14–35 W	2×10^4
T-8	58 W	1.4×10^4
T-8	36 W	1.1×10^4
T-12 bulb	Cool white 430 mA	8.2×10^3
T-12 bulb	Cool white 800 mA	1.1×10^4
T-12 bulb	Cool white 1500 mA	1.7×10^4
T-17 grooved	Cool white 1500 mA	1.5×10^4
Electroluminescent sources		
Green color at 120 V 60 Hz	—	27
Green color at 600 V 400 Hz	—	68
Carbon arc sources		
Plain carbon arc	Positive crater	1.5×10^8
High intensity carbon arc	13.6 Rotating positive carbon	1.0×10^9
Enclosed electric arc sources		
High pressure mercury	Type H33 2.5 atm	1.5×10^6
High pressure mercury	Type H38 10 atm	1.8×10^6
High intensity short arc mercury	30 atm	2.4×10^8 (4.3×10^9 peak)
Xenon short arc	900 W dc	1.8×10^8
Electronic flash tubes	900 W dc	1×10^9 to 3×10^9

Figure 6-2. Continued

Light Source		Approximate Average Luminance (cd/m ²)
Photographic flash units	In beam candlepower seconds	400–6,000+
Photographic flash units	(BCPS)	400–16,000+
Clear glass neon tube	15 mm 60 mA	1.6×10^3
Clear glass neon tube	15 mm 60 mA	8×10^2
Clear glass blue tube	15 mm 60 mA	8×10^2

in the design and adjustment of circuit breakers, in circuit fusing, in the design of lighting-circuit switch contacts, and in dimmer designs.

Color Temperature. Often it is important to know the apparent color temperature of an incandescent lamp. Figure 6-9 expresses the approximate relationship between color temperature and luminous efficacy for a range of gas-filled lamps. The efficacy value often can be found in the literature, or it can be calculated from published lumen and wattage data. From this value it is possible to approximate the average color temperature of the filament.

Construction and Assembly. Figure 6-10 shows the basic parts and steps in the assembly of a typical incandescent, general-service filament lamp. In miniature lamps three methods of construction are typically used: flange seal, butt seal, and pinch seal (Figure 6-11).

The flange seal generally is used with lamps 20 mm (0.79 in.) and larger in bulb diameter. This construction features a glass stem with a flange at the bottom that is sealed to the neck of the bulb. When used with bayonet bases, the plane of the filament and lead wires is normally at right angles to the plane of the base pins, but a tolerance of 15° generally is permitted. The advantages of this construction are: (1) heavy lead-in wires can be used for lamp currents up to 12 A, (2) the filament can be accurately positioned, and (3) sturdy stem construction resists filament displacement and damage from shock and vibration.

The butt seal is constructed as follows. A mount consisting of lead-in wires, bead, and filament is dropped into the open end of the bulb. The lead-in wires are bent to locate the filament at the desired distance from the bulb end. An exhaust tube is then dropped down and butted against the lead-in wire and glass bulb just prior to sealing and exhausting. The base, applied later, together with the basing cement, must not only provide the lamp contacts but also protect the delicate seal. Because of seal limitations, butt seal lamps are restricted to small wire sizes with a current limit of approximately 1.0 A. The filament position varies considerably more than in flange seal lamps, since there is no definite relationship between the planes of the filament and base pins. Occasionally butt seal lamps are used without bases; these lamps should be handled carefully. When used with a base, the advantages of butt seal construction are (1) low cost and (2) small size (usually 20 mm [0.79 in.] and below).

The pinch seal is so named because glass is pinched, or formed, around the lead-in wires. Two forms are used: wire

terminals and wedge base construction. For the smaller types of glow lamps, the bulb is exhausted and tipped off at the end opposite the lead-in wires. With newer wedge base lamps, the exhaust tip is at the bottom rather than the top. Pinch seal construction eliminates the need for a conventional base. Advantages are: (1) low cost; (2) small size; (3) with filament lamps, the elimination of solder and cement, which allows operation up to 300°C; and (4) small space required for wedge base lamps.

The molybdenum seal is used in some tungsten-halogen lamps, where wire seals cannot be employed, due to their thermal expansion mismatch with the fused silica envelope material. Molybdenum seals consist of thin ribbons or foils of molybdenum that are pinched in the base of the lamps to provide the required electrical lead-in. The ribbons provide a reliable seal as long as base temperature is kept below the molybdenum oxidation temperature of 350°C (662°F).

Filament Forms and Designations. Filament design involves a careful balance between light output and life. Filament forms, sizes, and support constructions vary widely with different types of lamps (Figure 6-12). Their designs are determined largely by service requirements. Filament forms are designated by a letter or letters followed by an arbitrary number. The most commonly used letters are: S (straight), meaning the wire is uncoiled; C (coiled), meaning the wire is wound into a helical coil; and CC (coiled coil), meaning the coil is itself wound into a helical coil. Coiling the filament increases its luminous efficacy; forming a coiled coil further increases efficacy. More filament supports are required in lamps designed for rough service and vibration service than for general-service lamps.

Bulbs

Shapes and Sizes. Common bulb shapes are shown in Figure 6-4.

Types of Glass. Most bulbs are made of regular lead or soda lime (soft) glass, but some are made of borosilicate heat-resisting (hard) glass. The latter withstand higher temperatures and are used for highly loaded lamps. They usually withstand exposure to moisture or luminaire parts touching the bulb. Three specialized forms of glass are also used as lamp envelopes: fused silica (quartz), high-silica, and aluminosilicate glass. These materials can withstand still higher temperatures. See the section "Bulb and Socket Temperature" below.

Figure 6-3. General Characteristics of Commonly Used Light Sources*
(This table is intended to show the wide range of parameters available for lamp products. A specific example has been chosen for each source type.)

Source Type and Correlated Color Temperature	Lamp Watts	Initial Lumens	Efficacy (LPW) ¹	Lumen Maintenance ²	Life (Hours)	CRI	Starting and Warmup Time ³ (Minutes)	Dimming Range (Percent Light Output)
Standard incandescent filament, 2700 K	100	1690	17	85	750	100	0	100-0
Tungsten-halogen (linear), 2950 K	300	6000	20	95	2000	100	0	100-0
Tungsten-halogen (reflector), 2850 K	90	1280 ⁴	14	95	2500	100	0	100-0
Tungsten-halogen (low voltage reflector), 3000 K-3200 K	50	900 ⁴	18	95	4000	100	0	100-0
Fluorescent T-5 4 ft., 3000 K-4100 K	28	2900 ⁴	104	95	20,000	85	0	100-1
High output fluorescent T-5 4 ft., 3000 K-4000 K	54	5000 ⁴	93	95	20,000	85	0	100-1
Fluorescent T-8 4 ft., 3000 K-4100 K	32	2800	88	85	20,000	75	0	100-1
Reduced wattage T-12 4 ft., 3500 K	34	2800	82	85	20,000	73	0	N/A ⁹
Slimline reduced wattage 8 ft., 3000 K-5000 K	60	6900	96	80	12,000	85	0	N/A ⁹
High output reduced wattage 8 ft., 4100 K	95	8000	84	75	12,000	62	0	100-1
Compact fluorescent (long twin), 3000 K-4100 K	38	3300	87	85	20,000	82	1	100-5
Compact fluorescent (double), 2700 K-4100 K	26	1800	70	85	10,000	82	1	100-5 ¹
Mercury vapor, 6800 K	175	7900	45	60	24,000	20	<10	100-10
Metal halide, low wattage, 3200 K	100	8075	81	85	10,000	70	<5	100-50 ⁶
Metal halide, high wattage, 4000 K	400	36,000	90	80	20,000	65	<10	100-50 ⁶
HPS, low wattage, 2100 K	70	6300	90	90	24,000	21	<5	100-50 ⁶
HPS, high wattage (diffuse), 2100 K	250	26,000	104	90	24,000	21	<5	100-50 ⁶

* See manufacturers' catalogs for specific data.

1. Efficacy for lamp is shown. Ballasting is required for all lamps except standard incandescent and tungsten-halogen.

2. Percent of initial lumens for illuminance calculations.

3. Time interval to reach usable light output.

4. Four-pin lamp required.

5. The important performance parameters for reflector lamps are beam angle and maximum center beam intensity.

6. Dimming below the lower value results in significant color shift.

7. Exact lamp length is 1149 mm.

8. Lumen output measured at 35°C (96°F) ambient.

9. Dimming ballasts are currently not available for this lamp.

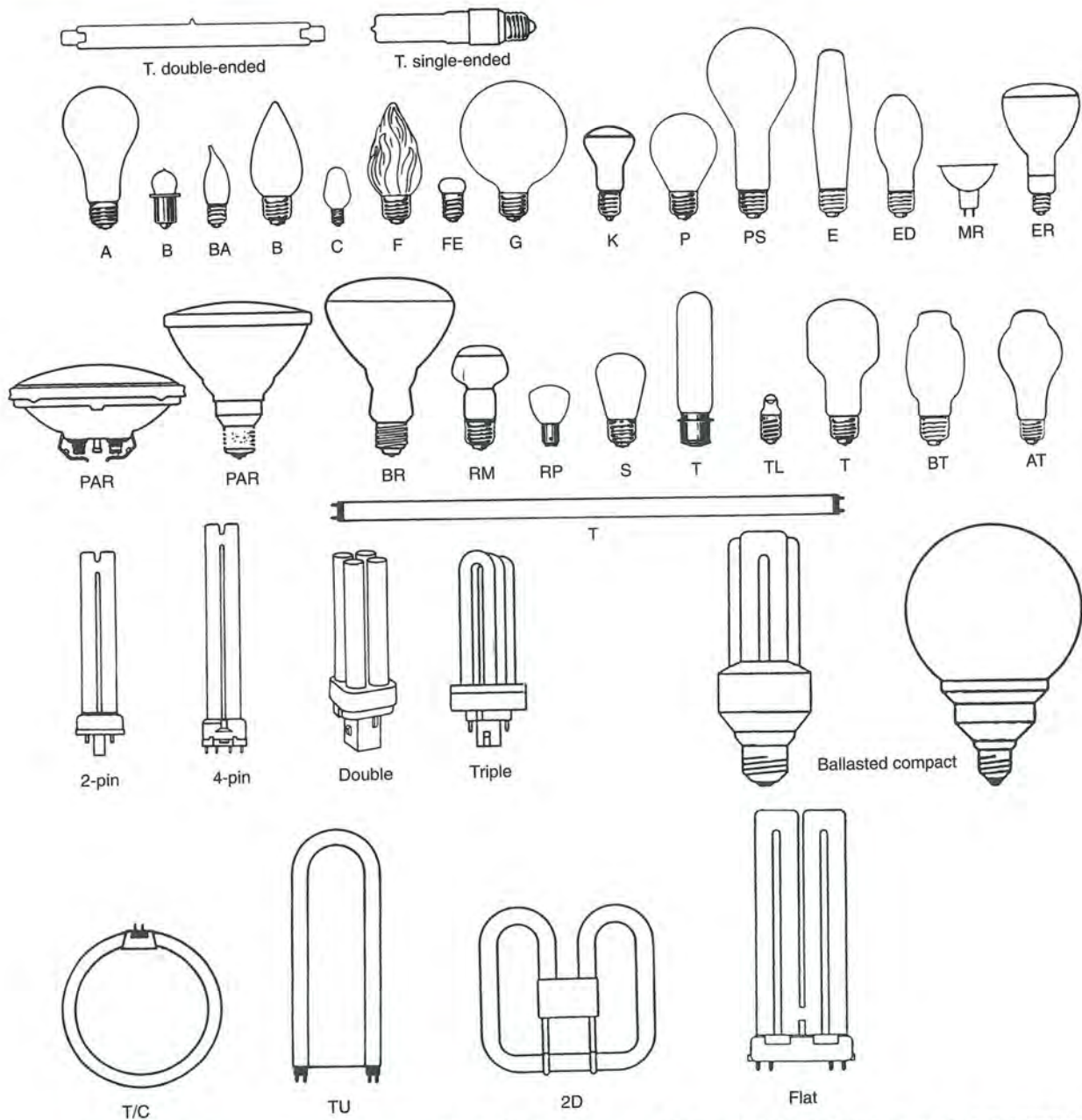


Figure 6-4. Typical bulb shapes (not to scale) and their ANSI designations. Not every ANSI designation, as key-listed here to a descriptive phrase or word, is illustrated.

A—Arbitrary spherical shape tapered to narrow neck
 AT—Arbitrary tubular
 B—Bulged or bullet shape; blunt tip
 BA—Bulged with angular (bent) tip
 BD—Bulged with dimple in crown
 BR—Bulged reflector
 BT—Bulged tubular
 C—Conical
 CA—Candle shape with bent tip
 CC—Two conical shapes blended together (formerly DC)
 E—Elliptical
 ED—Elliptical with dimple in the crown

ER—Elliptical reflector
 F—Flame shape, decorative
 FE—Flat elliptical
 G—Globe shape
 GT—Globe/tubular combination
 K—Similar to M but with conical transition
 M—Mushroom shape with rounded transitions
 MR—Multifaceted reflector
 P—Pear shape
 PS—Pear shape with straight neck
 PAR—Parabolic aluminized reflector
 R—Reflector

RB—Bulged reflector (see the more common BR above)
 RD—Reflector with dimple in crown
 REC—PAR type lamp with rectangular face
 RM—Reflector, mushroom shape
 RP—Reflector, pear shape
 S—Straight-sided shape (compare with CA and BA)
 ST—Straight-tipped shape
 T—Tubular shape
 TL—Tubular shape with lens in crown
 T/C—Tubular circular
 TU—Tubular U-shape
 2D—2-dimensional

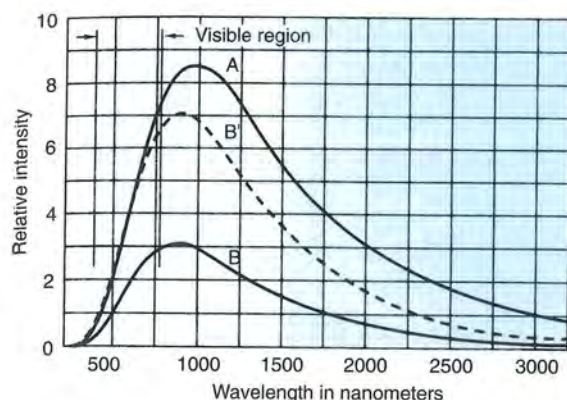


Figure 6-5. Radiating characteristics of tungsten. Curve A: radiant flux from one square centimeter of a blackbody at 3000 K. Curve B: radiant flux from one square centimeter of tungsten at 3000 K. Curve B': radiant flux from 2.27 square centimeters of tungsten at 3000 K (equal to curve A in visible region). (The 500-watt 120-volt general service lamp operates at about 3000 K.)

Bulb Finishes and Colors. Inside frosting is applied to many types and sizes of bulbs. It produces moderate diffusion of the light with very little reduction in output. The extremely high filament luminance of clear lamps is reduced, and striations and shadows are mostly eliminated. White lamps having an inside coating of finely powdered white silica provide a better diffusion with little absorption of light.

Daylight lamps have bluish glass bulbs that absorb some of the long wavelengths produced by the filament. The transmitted light is of a higher correlated color temperature. This color, achieved at the expense of approximately 35%

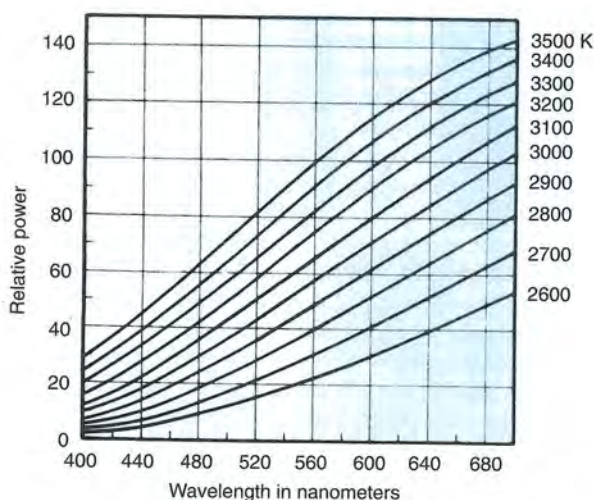


Figure 6-6. Spectral power distribution in the visible region from tungsten filaments of equal wattage but different temperatures.

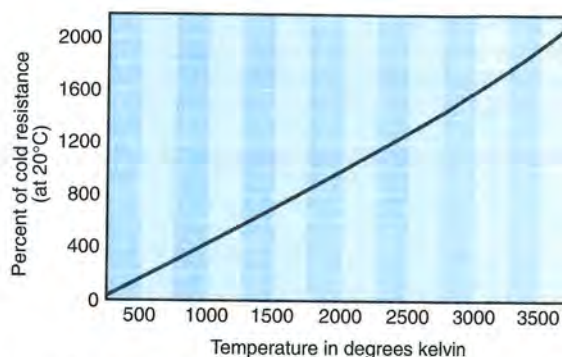


Figure 6-7. Variation of tungsten filament hot resistance with temperature.

reduction in light output through absorption, varies between 3500 and 4000 K. This is almost midway between tungsten filament light and daylight.

General-service incandescent colored lamps are available with inside- and outside-spray-coated, outside-ceramic, transparent-plastic-coated, and natural-colored bulbs. Outside-spray-coated lamps generally are used indoors and not

Figure 6-8. Effect of Hot-Cold Resistance on In-rush Current in an Incandescent Filament (Laboratory Conditions)

Lamp wattage	Voltage	Normal current (A)	Theoretical In-rush: Basis, hot-to-cold resistance (A)*	Time for current to fall to normal value (s)
General-service incandescent				
15	120	0.125	2.30	0.05
25	120	0.208	3.98	0.06
40	120	0.333	7.00	0.07
50	120	0.417	8.34	0.07
60	120	0.500	10.20	0.08
75	120	0.625	13.10	0.09
100	120	0.835	17.90	0.10
150	120	1.25	26.10	0.12
200	120	1.67	39.50	0.13
300	120	2.50	53.00	0.13
500	120	4.17	89.50	0.15
750	120	6.25	113.00	0.17
1000	120	8.30	195.00	0.18
1500	120	12.50	290.00	0.20
2000	120	16.70	378.00	0.23
Tungsten-halogen lamps (C-8 filament)				
300	120	2.50	62.00	†
500	120	4.17	102.00	†
1000	240	4.17	100.00	†
1500	240	6.24	147.00	†
1500	277	5.42	129.00	†

* The current will reach the peak value within the first peak of the supplied voltage. Thus the time approaches zero if the instantaneous supplied voltage is at peak, or it could be as much as 0.006 second.

† Not established. Estimated time is 5 to 20 cycles.

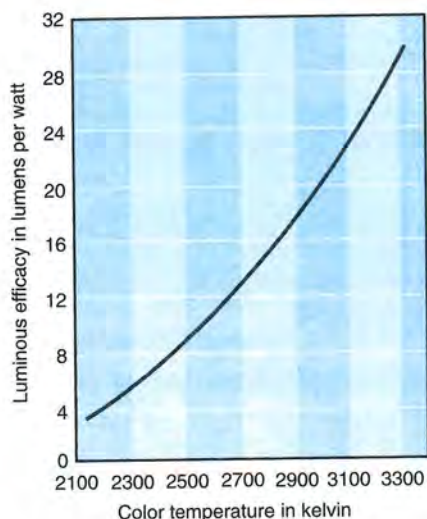


Figure 6-9. Variation of color temperature with lamp efficacy.

exposed to weather. Their surfaces collect dirt readily and are not easily cleaned. Inside-coated bulbs have smooth outside surfaces that are easily cleaned; thus the pigments are more durable. Ceramic-coated bulbs have the colored pigments fused onto the glass, providing a permanent finish. They are suitable for indoor and outdoor use, as are most transparent-plastic-coated bulbs. The coating permits the filament to be observed directly. Natural-colored bulbs are made of colored glass. Colored reflector lamps use ceramic-coated bulbs, stained bulbs, plastic-coated bulbs, and dichroic interference filters to obtain the desired color characteristics.

Bases. Figure 6-13 shows the most common lamp bases. Most lamps for general lighting purposes employ one of the screw bases. Where a high degree of accuracy in positioning of light sources with relation to optical elements is important, as in the case of projection systems, bipost and prefocus bases ensure proper filament location. Lamp wattage is also a factor in determining the base type.

Most bases are secured to the bulbs by cement and are cured by heat when the lamp is manufactured. Since this cement becomes weaker with age, particularly if exposed to excessive heat, lamps intended for high-temperature service use a special heat-tolerant basing cement or bases that are mechanically fastened without the use of cement.

Gas Fill. Around 1911, attempts were made to reduce the rate of evaporation of the filament by the use of gas-filled bulbs. Nitrogen was first used for this purpose.⁸ Although the fill gas reduced bulb-wall blackening, it increased heat loss, leading to even greater light loss. An incandescent filament operating in an inert gas is surrounded by a thin sheath of heated gas, to which some of the input energy is lost; the proportion lost decreases as the filament diameter is increased. When the filament is coiled in a tight helix, the

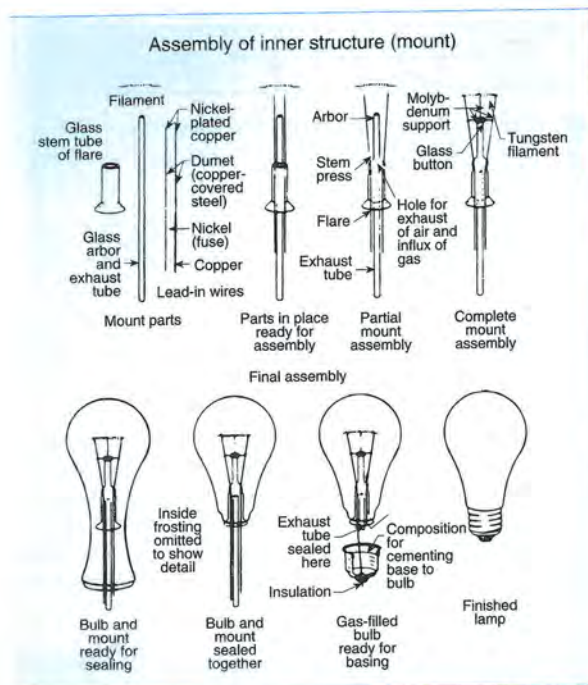


Figure 6-10. Steps in the manufacture of a typical incandescent filament lamp.

sheath surrounds the entire coil so that the heat loss is no longer determined by the diameter of the wire but by the diameter of the coil, thus greatly reducing this energy loss. A coiled-coil filament has even less length for a given power rating, thus further reducing the area available for convec-



Figure 6-11. Primary type of bulb construction: (a) glass halogen capsule with pinched seal, (b) pinch seal with lead-in wire terminals, (c) butt seal, (d) flange seal, and (e) molybdenum ribbon pinch seal.

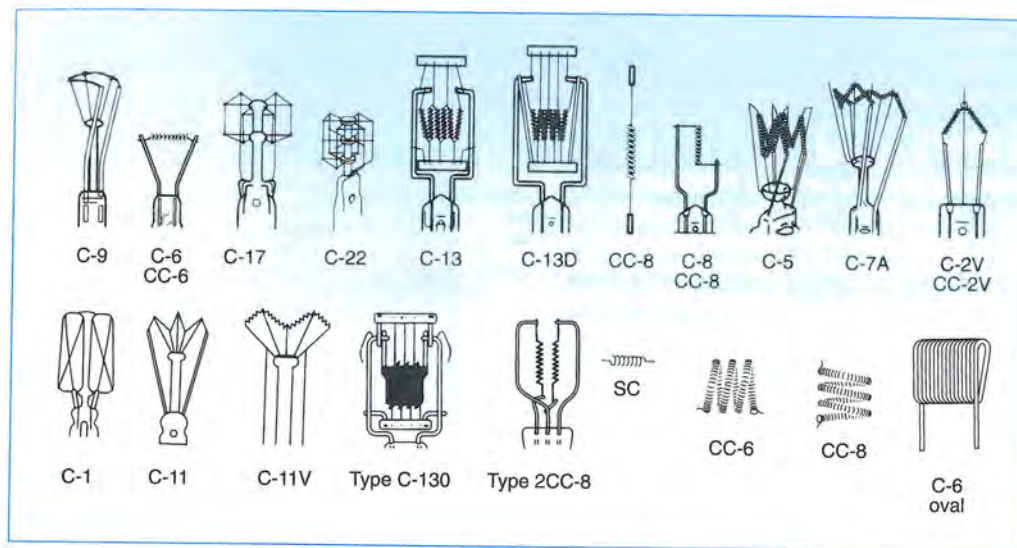


Figure 6-12. Typical lamp filament constructions (not to scale).

tive cooling. The use of coiled-coil filaments and gas-filled bulbs has yielded major improvement in incandescent lamp efficacies. However, general-service 120-V lamps below 25 W are usually of the vacuum type since gas filling does not improve the luminous efficacy in this wattage range.

Inert gases are now preferred because they do not react with the internal parts of the lamp and because they conduct less heat than nitrogen. It was some years after the development of gas-filled lamps before argon became available in sufficient quantity and purity and at reasonable cost. Most lamps are now filled with argon and a small amount of nitrogen; some nitrogen is necessary to suppress arcing between the lead-in wires.

The proportion of argon and nitrogen depends on the voltage rating, the filament construction and temperature, and the lead-tip spacing. Typical amounts of argon in use are: 99.6% for 6-V lamps, 95% for 120-V general-service coiled-coil lamps, 90% for 230-V lamps having fused lead wires, and 50% or less for 230-V lamps when no fuses are used in the leads. Some projection lamps are 100% nitrogen filled.

Krypton, although expensive, is used in some lamps where the increase in cost is justified by the increased efficacy or increased life. Krypton gas has lower heat conductivity than argon. Also, the krypton molecule is larger than that of argon and therefore further retards the evaporation of the filament. Depending on the filament form, bulb size, and mixture of nitrogen and argon, krypton fill can increase efficacy by 7 to 20%.^{9,10} Krypton is used in some special lamps such as marine signal and miner's cap lamps because of the resulting high efficacy.

An even more expensive gas, xenon, is used in a number of unique applications. Xenon has lower heat conductivity and larger molecular size than krypton and thus allows even

higher efficacy. However, it costs significantly more than krypton and is used only for special product applications.

Hydrogen gas has a high heat conductivity and is therefore useful for signaling lamps where quick flashing is desired.¹¹

Tungsten-Halogen Lamps. The light generation mechanism of tungsten-halogen lamps is the same as that of common incandescent filament lamps, except for the halogen regenerative cycle. Halogen is the name given to a family of electronegative elements, including bromine, chlorine, fluorine, and iodine. Although the tungsten-halogen regenerative cycle has been understood for many years, no practical method of using it was established until the development of small-diameter fused quartz envelopes for filament lamps provided the proper temperature parameters. Iodine was used in the first tungsten-halogen lamp; today, other halogen compounds, predominantly bromine, are used.

The regenerative cycle starts with the tungsten filament operating at incandescence, evaporating tungsten off the filament. Normally the tungsten particles would collect on the bulb wall (Figure 6-14a), resulting in bulb blackening, common with incandescent lamps and most evident near the end of their life. However, in halogen lamps the temperature of the bulb is high enough so that the tungsten combines with the halogen. The correlated minimum temperature of the bulb must be approximately 260°C (500°F).

The resulting tungsten-halogen compound is also gaseous and continues to circulate inside the lamp until it comes in contact with the incandescent filament. Here, the heat is sufficient to break down the compound into tungsten, which is redeposited on the filament, and halogen, which is freed to continue its role in the regenerative cycle (Figure 6-14b). However, since the tungsten does not necessarily redeposit

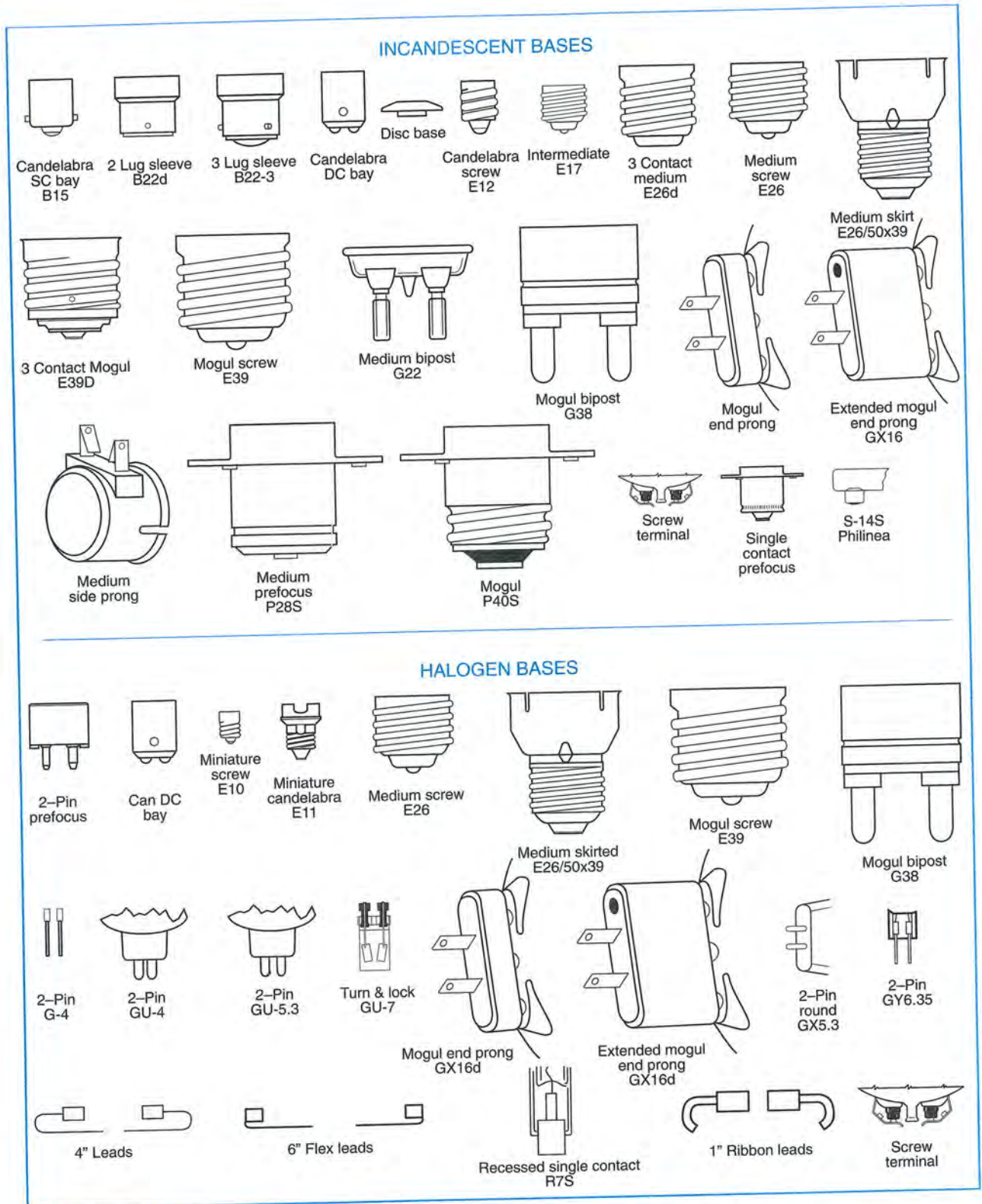
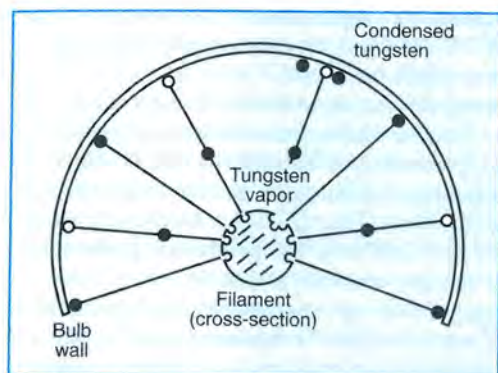
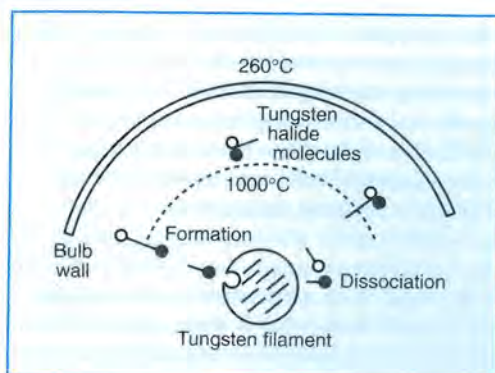


Figure 6-13. Common lamp bases (not to scale). ANSI designations are shown, where available.



a



b

Figure 6-14. Tungsten cycle in (a) standard incandescent, and (b) tungsten-halogen.

exactly where it came from, the tungsten-halogen lamp still has a finite life. Dimmed tungsten-halogen lamps should periodically be run at full power, inducing the tungsten-halogen cycle to clean the tungsten off the bulb wall, and thereby maintaining lamp efficacy over time.

The requirement of a high bulb wall temperature for the halogen regenerative cycle led to the corollary effect of producing smaller lamps. This resulted first in the development of small low-voltage reflector lamps and finally in the incorporation of halogen capsules in various PAR envelopes. These PAR envelopes have replaced both incandescent PAR and BR types.

Performance Parameters

Energy Characteristics. The manner in which the energy input to a lamp is dissipated can be seen in Figure 6-15 below for typical general-service lamps. The radiation in the visible spectrum (column 2) is the percentage of the input power actually converted to visible radiation. The gas loss (column 4) indicates the amount of heat lost by the filament due to the conduction through and convection by the surrounding gas in gas-filled lamps. The end loss (column 6) is the heat lost from the filament by the lead-in wires and support hooks which conduct heat from the filament. Column 3 shows the total radiation beyond the bulb, which is less than the actual filament radiation due to absorption by the glass bulb and the lamp base.

Incandescent lamps operated below 25 Hz will produce perceptible flicker and can create a stroboscopic effect. Flicker will be less from an incandescent source if it has a larger filament and is operated at a higher wattage and at a higher supply frequency. Modern incandescent light sources operated at 60 Hz do not produce noticeable flicker, nor a stroboscopic effect,

Figure 6-15. Luminous and Thermal Characteristics of Typical Incandescent Filament Lamps

Watts	Radiated in visible spectrum (percent of input wattage)	Total filament radiation beyond bulb (percent of input wattage)	Gas loss (percent of input wattage)	Base and bulb loss (percent of input wattage)	End loss (loss by conduction at filament ends in percent of input wattage)	Filament heat current (J)	Heating time to 90 percent lumens (s)	Cooling time to 10 percent lumens (s)
6*	6	93.0	—	5.5	1.5	0.25	0.04	0.01
0*	7.1	93.5	—	5.0	1.5	0.62	0.06	0.02
5*	8.7	94.0	—	4.5	1.5	2.8	0.10	0.03
40†	7.4	71.3	20.0	7.1	1.6	2.5	0.07	0.03
60‡	7.5	80.8	13.5	4.5	1.2	5.5	0.10	0.04
100‡	10.0	82.0	11.5	5.2	1.3	14.1	0.13	0.06
200†	10.2	77.4	13.7	7.2	1.7	39.5	0.22	0.09
300†	11.1	79.8	11.6	6.8	1.8	80.0	0.27	0.13
500†	12.0	82.3	8.8	7.1	1.8	182.0	0.38	0.19
1000†	12.1	87.4	6.0	4.7	1.9	568.0	0.67	0.30

* Vacuum.

† Coiled—coil filament.

‡ Gas-filled.

Figure 6-16. Flicker Characteristics of Incandescent Filament Lamps

Watts	Percent Flicker		Flicker Index	
	60 Hz	25 Hz	60 Hz	25 Hz
6*	29	69	0.092	0.220
10*	17	40	0.054	0.127
25*	10	28	0.032	0.089
40+	13	29	0.041	0.092
60#	8	19	0.025	0.060
100#	5	14	0.016	0.045
200+	4	11	0.013	0.035
300+	3	8	0.010	0.025
500+	2	6	0.006	0.019
1000+	1	4	0.003	0.013

* Vacuum.

+ Coiled-coil filament.

Gas-filled.

to the human eye. The flicker index of several incandescent lamps operated at 25 Hz and 60 Hz is shown in Figure 6-16. Consult Chapter 2, Measurement of Light and Other Radiant Energy, for more information about lamp flicker.

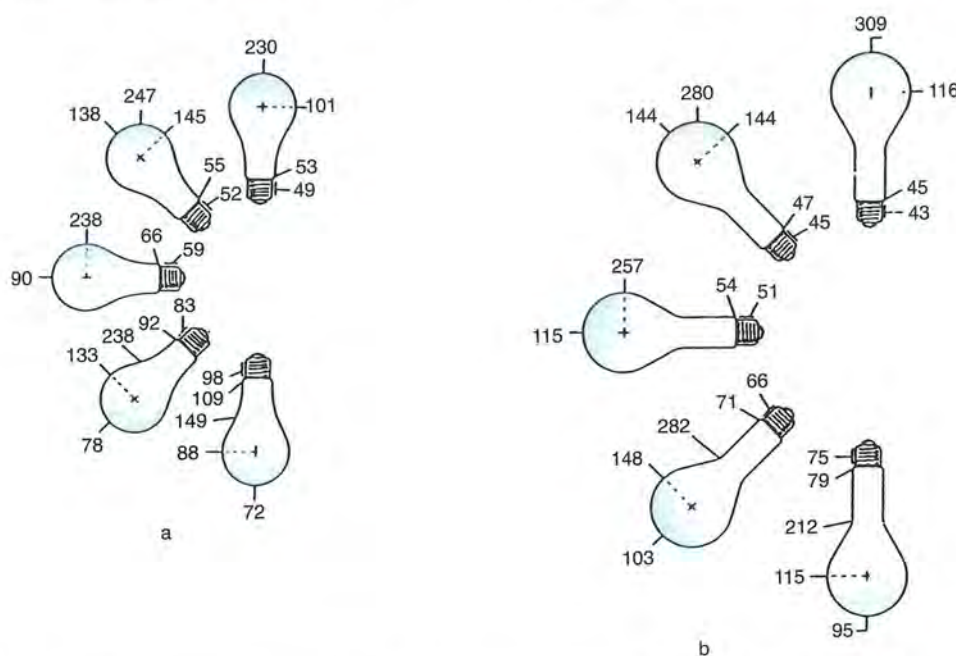
Bulb and Socket Temperatures. Incandescent filament lamp operating temperatures are important for several reasons. Excessive lamp temperature can affect lamp life, luminaire life, and the life of the electrical supply circuit. High temperatures can ignite combustible materials that form a part of the luminaire or those adjacent to the luminaire. Under certain atmosphere or dust conditions, high bulb temperatures (above 160°C [320°F]) can induce explosion or fire.

Bulb and socket temperatures for a 100-W A-19 lamp and a 500-W PS-35 lamp for different operating positions are shown in Figure 6-17.

General-service incandescent filament lamp bulbs are made of regular lead or lime soft glass, the maximum safe operating temperature of which is 370°C (698°F). Some lamps for special applications, such as outdoor floodlighting lamps, have hard glass bulbs that have a safe temperature limit of 470°C (878°F). Lamps with still harder glass bulbs can be operated up to 520°C (968°F).

The maximum safe base temperature for general-service lamps is 170°C (338°F), measured at the junction of the base and the bulb. In all cases excessive temperature can cause failure of the basing cement, as well as softening of the solder used to connect the lead wires to the base. Silicone cement and high-melting-point solder permit base temperatures to approach 260°C (500°F). Bipost bases carry considerable heat to the socket through the base pins, and the parts of the socket in contact with the base pins should be capable of withstanding temperatures up to 290°C (554°F). Tubular fused quartz infrared and tungsten-halogen cycle lamps generally have a maximum seal temperature of 350°C (662°F) to prevent oxidation.

Some of the factors affecting base temperature are filament type, light center length, heat shields, bulb shape and size, and gas fill. Base temperature is not necessarily correlated to wattage ratings; that is, lamps of lower wattage do not necessarily have lower base temperatures. Medium-base luminaires should be capable of accepting lamp base temperatures on the order of 135–150°C (275–302°F). These

**Figure 6-17.** Incandescent filament lamp operating temperatures in still air at 25°C (77°F) ambient: (a) 100-watt CC-8, A-19 lamp; (b) 500-watt CC-8, PS-35 lamp. All lamp temperatures shown are in degrees Celsius.

limits are consistent with Canadian Standards Association (CSA), American National Standards Institute (ANSI), and International Electrotechnical Commission (IEC) standards for base temperature for A-type lamps. Measurements should be made in accordance with ANSI C78.25, "Lamp-Base Temperature Rise-Method of Measurements."¹² If the luminaire accepts R and PAR lamps, then the temperature capability of the luminaire should be 170 to 185°C (338 to 365°F) if reasonable electrical insulation life is desired for the luminaire. Heat-transmitting dichroic-reflector lamps should be placed only in luminaires specifically designed for them; this is normally indicated on the luminaire.

For base-up operation, and where only slight enclosing of the lamp is provided by the luminaire, base temperature is the major factor affecting luminaire temperatures, with lamp wattage being a minor consideration. As the luminaire provides more and more enclosing of the lamp, base temperature has less effect, and wattage assumes more importance.

High temperatures reduce the life of electrical insulation for lamp and luminaire parts. Figure 6-18 shows how the position of the filament affects the temperature of the bulb. This variation in temperature with position is sufficiently large to affect the life of wire insulation and other luminaire components.

Lamp Characteristics

Life, Efficacy, Color Temperature, and Voltage Relationships. If the voltage applied to an incandescent filament lamp is varied, there is a resulting change in the filament resistance and temperature, current, power, light output, efficacy, and life. These characteristics are interrelated, and not one of them can be changed without affecting the others. The following equations can be used to calculate the effect of a change from the design conditions on lamp performance (capital letters represent normal rated values; lower-case letters represent changed values):

$$\frac{\text{life}}{\text{LIFE}} = \left(\frac{\text{VOLTS}}{\text{volts}} \right)^d$$

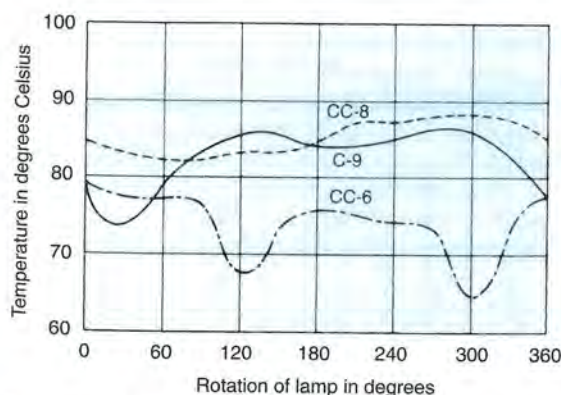


Figure 6-18. Profile temperatures vary with rotation of lamp filament; three types shown.

$$\frac{\text{lumens}}{\text{LUMENS}} = \left(\frac{\text{volts}}{\text{VOLTS}} \right)^k$$

$$\frac{\text{lpw}}{\text{LPW}} = \left(\frac{\text{volts}}{\text{VOLTS}} \right)^g$$

$$\frac{\text{watts}}{\text{WATTS}} = \left(\frac{\text{volts}}{\text{VOLTS}} \right)^n$$

$$\frac{\text{color temperature}}{\text{COLOR TEMPERATURE}} = \left(\frac{\text{volts}}{\text{VOLTS}} \right)^m$$

For approximations, the following exponents may be used in the above equations: $d = 13$, $g = 1.9$, $k = 3.4$, $n = 1.6$, and $m = 0.42$. For more accuracy, the exponents must be determined by each lamp manufacturer from a comparison of normal-voltage and over- or undervoltage tests of many lamp groups. Exponents vary for different lamp types, lamp wattages, and ranges of percentage voltage variation. The values given above are roughly applicable to vacuum lamps of approximately 10 lm/W and gas-filled lamps of approximately 16 lm/W in a voltage range of 90 to 110% of rated voltage. For information outside this range, refer to Figure 6-19.

The curves of Figure 6-19a show the effect of voltage variations on lamps in general lighting (multiple) circuits.^{13,14} The effect of voltage variation on the characteristics of tungsten-halogen lamps cannot be accurately predicted outside of the voltage range of 90 to 110% of the rated voltage.

Filament Notching. Ordinarily, for laboratory test operation, normal tungsten filament evaporation determines incandescent lamp life. Where that is so, lamps should reach their design-predicted life. Another prominent factor influencing filament life is filament notching. Filament notching is the appearance of steplike or sawtooth irregularities on all or part of the tungsten filament surface after long use. These notches reduce the filament wire diameter at random points. In some cases, especially for fine-wire filaments, the notching is so deep as to almost sever the wire. Faster spot evaporation due to high temperatures at this notch and reduced filament strength become the dominant factors influencing lamp life. Predicted lamp life can be reduced by as much as one-half from this cause.

Filament notching is associated with at least three factors (primarily occurring in fine-wire filament lamps): (1) low-temperature filament operation, as in long-life lamps with 10,000- to 100,000-h designs; (2) small filament wire sizes, typically less than 0.025 mm (0.001 in.) in diameter; and (3) direct current operation.

Depreciation During Life. Over a period of time, incandescent filaments evaporate and become smaller, which increases their resistance. In multiple circuits, the increase in filament resistance reduces current, power, and light. A further reduction in light output is caused by the absorption of light by the deposit of the evaporated tungsten particles on the bulb.

In series circuits having constant-current regulators, the

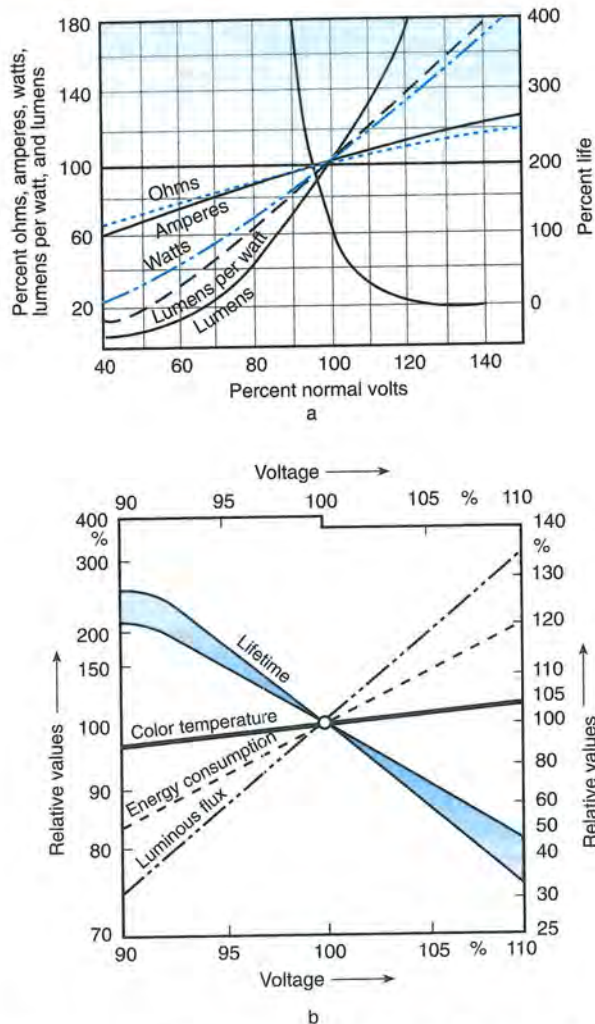


Figure 6-19. Effect of voltage and current variation on the operating characteristics of: (a) incandescent filament lamps in general lighting (multiple) circuits and (b) tungsten-halogen lamps in series street lighting circuits.

increase in filament resistance during life causes an increase in the voltage across the lamp and a consequent increase in wattage and generated lumens. This increase in lumens is offset to varying degrees by the absorption of light by the tungsten deposit on the bulb. In low-current lamps the net depreciation in light output during life is very small, or in the smaller sizes there may be an actual increase. In lamps of 15- and 20-A ratings, the bulb blackening is much greater, and throughout life more than offsets the increase in lumens due to the increased wattage.

The blackening in vacuum lamps is uniform over the bulb. In gas-filled lamps the evaporated tungsten particles are carried by convection currents to the upper part of the bulb. When gas-filled lamps are burned base up, most of the

blackening occurs on the neck area, where some of the light is normally intercepted by the base. Consequently, the lumen maintenance for base-up operating is better than for base-down or horizontal operating with gas-filled lamps.

In a base-up operating lamp, an appreciable reduction of lamp lumen depreciation (LLD) can be obtained through the use of a coiled-coil filament located on or parallel to the bulb axis.

To reduce blackening from traces of oxygen or water vapor in the gas fill, an active chemical, known as a getter, is used inside the bulb to combine with and absorb impurities remaining in the bulb.

Tungsten-halogen cycle lamps generally have significantly less depreciation during life due to the regenerative cycle, which removes the evaporated tungsten from the bulb and redeposits it on the filament. Figure 6-20 shows the change in light output and efficacy for typical incandescent and tungsten-halogen lamps. See the discussion on tungsten-halogen lamps earlier in this chapter.

Lamp Mortality. Many factors inherent in the manufacturing process make it impossible for every lamp to achieve the rated life for which it was designed. For this reason, lamp life is rated as the average of a large group. A range of typical mortality curves representing the performance of high-quality lamps is illustrated in Figure 6-21.

Dimming of Incandescent and Tungsten-Halogen Lamps. Dimmers today have a dual purpose: energy conservation and aesthetic lighting effects. Incandescent lamps can be dimmed simply by lowering the voltage across the lamp filament. When the voltage is lowered, less power is dissipated and less light is produced with a lower color tempera-

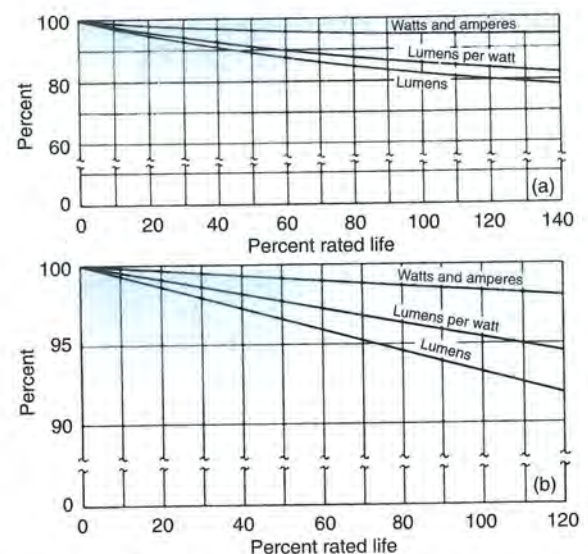


Figure 6-20. Typical operating characteristics of lamps as a function of burning time: (a) general-service lamps and (b) tungsten-halogen lamps. (Note differences in scales.)

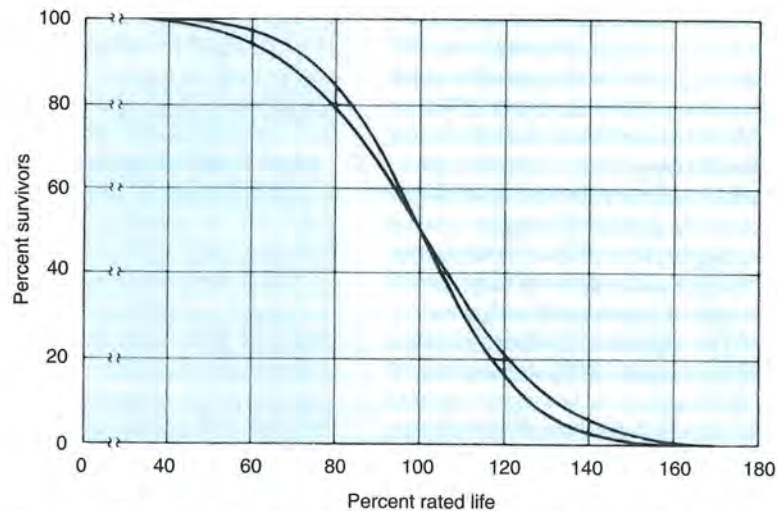


Figure 6-21. Range of typical mortality curves (average for a statistically large group of incandescent filament lamps).

ture. An added benefit is an increase in the life of an incandescent lamp. For example, when an incandescent lamp is operated at 80% rated voltage using a dimmer, its life is increased by a factor of nearly 20. In a tungsten-halogen lamp, the life of the filament depends on voltage just as with standard incandescent filament lamps. However, because the regenerative halogen cycle stops when bulb wall temperature falls below 260°C (500°F), the tungsten halogen lamp blackens and its useful life is not extended by nearly the same factor as that of standard lamps. This can be partially compensated for by periodically operating the lamp near or at full light output, which helps clean the lamp of tungsten deposits.

In the 1950s, rheostats were used for dimming by regulating the lamp current in an incandescent lamp. They were large and inefficient. Today, most dimmers are electronic, using thyristor and transistor circuits that have low power dissipation. Modern dimmers are efficient and reduce power as the source is dimmed. Thyristors operate as high-speed switches that rapidly turn the voltage to the lamp on and off. This switching can cause electromagnetic interference with other electrical equipment as well as audible buzzing in the lamp filament. Magnetic coils known as chokes are usually used as filters to reduce these effects. With many wall-box dimmers, however, lamp buzzing cannot be completely eliminated because a larger choke is needed than space allows. For these cases, remotely mounted, properly sized lamp debuzzing coils or additional chokes are recommended.

Classification of Incandescent and Tungsten-Halogen Lamps

Incandescent filament lamps were historically divided into three major groups: large lamps, miniature lamps, and specialty lamps. They also were cataloged separately by lamp

manufacturers. There is no sharp dividing line among the groups, and they are usually included in the same catalog by the manufacturer. The discussion below classifies lamps into four categories for the purposes of illustrating their applications: general lamps, dedicated application lamps, low-voltage miniature and sealed beam lamps, and photographic and photo-optical lamps. The following gives a brief description of a few of the many types of lamps that are regularly manufactured. More complete details are available in manufacturers' catalogs.

General Lamps (Lamps Used in a Variety of Applications)

General Service. These are large lamps made for general lighting use on 120-V circuits. General-service lamps range from 10 to 1500 W and satisfy the majority of incandescent lighting applications. All sizes are made in both clear and inside-frosted bulbs. Below 200 W, inside-white-coated finishes are also available.

High Voltage. This voltage class refers to lamps that operate directly on circuits of 220 to 300 V and represents a very small portion of the lamp demand in North America. Lampholders should be Underwriters Laboratories (UL) or CSA approved for a voltage level appropriate to the voltage rating of the lamps being used, that is, 250 V for lamps up to 250 V, 600 V for lamps above 250 V.

High-voltage lamps have filaments of small diameter and longer length and require more supports than corresponding 120-V lamps. Therefore, they are less rugged and are 25 to 30% less efficient because of greater heat losses. Due to the higher operating voltage, these lamps require less current for the same power, permitting some wiring economy.¹⁵

Extended Service. Extended-service lamps are intended for use in applications where a lamp failure causes signifi-

cant inconvenience, nuisance, or hazard, or where replacement labor cost is high or power cost is unusually low. For such applications, where long life is most important and a reduction of light output is acceptable, lamps with 2500-h or longer rated life are available. Longer life is obtained by operating the filament at lower temperatures than normal. This, however, lowers the luminous efficacy. In most general-service use the cost of power used during the lamp life is many times the lamp life cost, and therefore efficacy is important. Where replacement of burned-out lamps is an easy, convenient operation, as in residential use, long-life lamps usually are not recommended.¹⁶ For such use, incandescent lamps with the usual 750- or 1000-h design life give a lower cost of light than extended-service lamps.

General-Lighting Tungsten-Halogen Lamps. These lamps improve on the regular incandescent sources in several ways. Their advantages over regular incandescent lamps include low LLD and compactness. They also provide whiter light (higher color temperature) and longer life at a given light output.

Halogen lamps are available in both line voltage and low voltage designs. The line voltage products are available as single ended, double ended, and PARs. The low voltage types are generally capsules or small reflector types. For specialty applications, other voltage ratings (e.g., 84 V, 200 V) are also available.

Low voltage halogen lamps operate in the voltage range from 5 to 30 V. This voltage is supplied through a step-down transformer. The advantages of low-voltage lamps are greater resistance to vibration and shock because of their larger diameter filament wire, a more compact filament that allows better beam control, and higher efficacy than line voltage lamps.

There is more ultraviolet (UV) radiation generated from tungsten-halogen lamps than from regular incandescent lamps, due to the higher filament temperature. The amount of UV radiation emitted is determined by the envelope material. Fused quartz and most high-silica glass transmit most of the UV radiated by the filament, while other special high-silica glass and aluminosilicate glass absorb UV radiation. In general lighting applications, luminaires for tungsten-halogen lamps should have a lens or cover glass that, in addition to providing the required safety protection in case of lamp breakage, filters out most of the UV radiation. In applications where the reduction of UV radiation is critical, additional filtering might be required. Care should be taken when applying lamps operating at correlated color temperatures above 3100 K, since both ultraviolet and short-wavelength visible radiation increase with color temperature,¹⁷ creating potential hazard for both people and objects.

The halogen regenerative cycle is very temperature sensitive. Operating lamps at voltages above or below manufacturer's recommendations can have adverse effects on the internal chemical processes. It is also important to follow manufacturer's recommendations as to operating position, bulb handling, and luminaire temperatures.

The higher pressures used allow tungsten-halogen lamps to be designed for higher efficacy and longer life than normal incandescent lamps of the same wattage. For example, the 500-W nonregenerative cycle lamp is rated at 10,600 lm for 1000 h, while the 500-W T-3 tungsten-halogen lamp is rated at 10,950 lm for 2000 h.

The development of high-performance glass tubings has led to the use of halogen glass capsules in PAR lamps, including PAR 16, PAR 20, PAR 30, and PAR 38.

Multilayer infrared reflective coatings can be applied to both quartz and glass halogen bulbs. These coatings transmit light and reflect infrared energy back to the filament. This reduces the input power required to reach a given filament temperature. Luminous efficacies of 27.0 to 35.6 lm/W are obtained with this technique without reducing life.

Reflector. Reflector lamps include those made in standard and special bulb shapes and have a reflective coating applied directly to part of the bulb surface. Both silver and aluminum coatings are used.¹⁸ Silver coatings can be applied internally or externally, and in the latter case the coating is protected by an electrolytically applied copper coating and sprayed aluminum finish. Aluminum coatings are applied internally by condensation of vaporized aluminum on the bulb surface. The following reflector lamps are readily available: bowl reflector lamps, neck reflector lamps, reflector spot and reflector flood lamps in R-type bulbs (certain sizes of reflector lamps are available with heat-resisting glass bulbs), and ellipsoidal reflector lamps (ER types), which allow substantially improved efficiency in deep, well-shielded downlights.¹⁹ PAR spot and PAR flood lamps use PAR bulbs, typically constructed from two molded glass parts, the reflector and the lens, which are fused together. As the names suggest, several lamp designs with different candlepower distributions are available, typically expressed in terms of beam angle. Colored R and PAR lamps are available. Cool beam PAR lamps with heat-transmitting dichroic reflectors are available where it is desirable to reduce the infrared energy in the beam. Long-neck halogen PAR-30 lamps are available for retrofitting standard R-30 luminaires without the use of socket extenders. Multifaceted pressed glass reflector lamps with tungsten-halogen capsules and infrared-transmitting dichroic reflectors, known as MR-11 and MR-16, have been adapted from projection lamp designs for display lighting applications.

Rough Service. To provide the resistance to filament breakage, rough-service lamps employ special, multiple-filament-support construction (C-22 in Figure 6-12). Because of the number of supports, the heat loss is higher and the efficacy lower than for general-service lamps.

In using miniature lamps where rough-service conditions are encountered, bayonet and wedge base lamps should be chosen instead of screw base lamps. Bayonet and wedge base lamps lock in the socket; screw base lamps tend to work loose.

Linear Incandescent. The linear incandescent lamp has a tubular bulb diameter of 26 mm (1 in.) and two metal disk

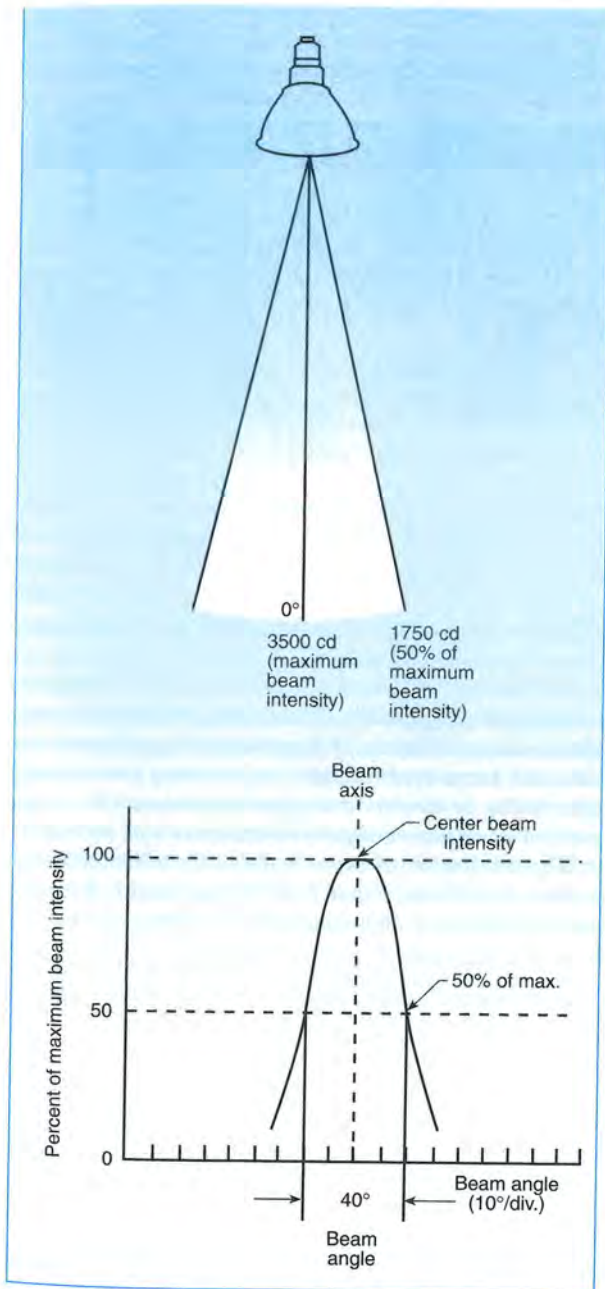


Figure 6-22. The beam angle is the angle within which the lamp produces 50% of the lamp's maximum intensity.

bases, one at each end of the lamp, with the filament connected between them. Many have adjustable insert tabs attached to the bases, thereby simplifying insertion into their sockets. The filament, in the form of a stretched coil, is supported on glass insulating beads along a small metal channel within the bulb. The 30- and 60-W sizes are available in the

450-mm (18-in.) length. The 40-W lamp is made in a 300-mm (12-in.) length. All sizes are available in either clear or inside-frosted tubes as well as white and various color coatings.

Another style of linear incandescent lamp, using the S14 base, is available. Versions include 35, 60, and 150 W.

Decorative. A wide variety of lamps for decorative application is available. Different bulb shapes, together with numerous colors and finishes, are used to achieve the desired appearance. Lamp manufacturers' catalogs should be consulted for information on the many decorative types.

Three-Way. These lamps employ two filaments, operated separately and in combination, to provide three light levels. The common lead-in wire is connected to the shell of the base; the other end of one filament is connected to a ring contact, and the end of the other filament to a center contact. Thus, either filament, or both together, may be used with the selection made in the socket. Three-way lamps are available in several different wattage combinations.

Energy-Saving. Most general- and extended-service lamps are now available in reduced wattages, which also have lower lumen output. The use of reflector lamps to improve directional lighting has also become popular for energy-saving applications. Better optical control with sharper cutoffs places the same illuminance on a specific area with fewer watts. A variety of reflector lamps is now available, including the BR30 and BR40. The most significant energy improvement is in the family of halogen PAR and halogen IR PAR products, which use significantly less power and provide equal or superior illuminance than incandescent PAR and BR types. In traffic signals, lamps are now being marketed with a ring mirror so as to capture lost light and redirect it through the lens.

Dedicated Application Lamps. Dedicated application lamps are those that have been designed primarily for a single application.

Spotlight and Floodlight. Lamps used in spotlights, floodlights, and other specialized luminaires for lighting theater stages, motion picture studios, and television studios, have concentrated filaments accurately positioned with respect to the base. When the filament is placed at the focal point of a reflector or lens system, a precisely controlled beam is obtained. These lamps are intended for use with external reflector systems. Because of their construction, these lamps must be burned in positions for which they are designed, to avoid premature failures.

Appliance Lamps. High-temperature types that can withstand temperatures up to 315°C (599°F) are available for ovens. Other types are designed for refrigerators, and rugged filament types are used in vacuum cleaners.

Vibration Service. Most lamps have coiled filaments made of tungsten with high sag resistance. Vibration lamps, designed for use where vibrations would cause early failure, are made with a more malleable tungsten filament. The sagging of the wire used allows the coils to open up under vibration, thus preventing short circuits between coils.

To withstand shock and vibration, low-voltage (6.3-V or less) miniature radio panel lamps incorporate mounts whose resonant frequency has been synchronized with that of the coiled filament.

Sometimes only trial and error will determine the best lamp to resist shock and vibration. Vibration-resistant sockets or equipment, using a coiled spring or other flexible material to deaden vibration, have been employed where general-service lamps are used under conditions of severe vibration.

Showcase. Display cases in retail applications commonly use tubular bulbs with conventional screw bases. The longer lamps have filaments with supports similar to linear incandescent lamps. The common sizes are 25 and 40 W, but sizes up to 75 W are available.

Sign. While large numbers of gas-filled lamps are used in enclosed and other types of electric signs, those designated particularly as sign lamps are mostly of the vacuum type. These lamps are best adapted for exposed sign and festoon service because the lower bulb temperature of vacuum lamps minimizes the occurrence of thermal cracks resulting from rain and snow. Some low-wattage lamps, however, are gas filled for use in flashing signs. Bulb temperatures of these low-wattage, gas-filled lamps are sufficiently low to permit exposed outdoor use on high-speed flashing circuits.

Traffic Signal Lamps. Lamps used in traffic signals are subjected to more severe service requirements than in most applications of incandescent lamps. Such lamps must be compatible with the design requirements of standard traffic signals.

Ribbon Filament Lamps. Incandescent lamps made with ribbons or strips of tungsten for the filaments have been used in special applications where it is desirable to have a substantial area of fairly uniform luminance.²⁰ Ribbon dimensions vary from 0.7 to 4 mm (0.03 to 0.16 in.) in width and up to 50 mm (1.97 in.) in length. The 5-20-A ribbon filament lamps are usually employed in recorders, instruments, oscillographs, and microscope illuminators. The 30- to 75-A lamps are used for pyrometer calibration standards and for spectrographic work. Figure 6-23 shows typical lamps.

Infrared Heat Lamps. All incandescent filament lamps are effective generators of infrared (IR) radiation. Most of the incandescent filament lamp input power is radiated as IR energy. Wavelengths longer than 5000 nm are absorbed to a large extent by the glass or fused quartz envelope. Lamps for heating applications are designed for low light output and long life. Tubular fused quartz lamps are also available with a ceramic reflector that increases heat by approximately 50% directly below the center line of the lamp.

Tungsten filament IR lamps are available with ratings up to 5000 W. Generally speaking, tungsten filament lamps for industrial, commercial, and residential service operate at a filament color temperature of 2500 K. At this low operating temperature compared to lighting lamp filament temperatures, the service life is well in excess of 5000 h. Frequently, lamps using tungsten filaments have provided many years of operation because the service life is generally determined by mechani-



Figure 6-23. Typical ribbon filament lamps: (a) 6-volt, 18-ampere, T-10, 2-mm, 3000-K microscope illuminator; (b) 6-volt, 9-ampere, T-8½, 1-mm, 3000-K optical source; and (c) 3.5-volt, 30-ampere, T-24 with quartz window, 3-mm, U-shaped filament, 2300-K pyrometer and spectroscopy source.

cal breakage or rupture of the filament due to vibration or handling, rather than the rate of evaporation of tungsten, as is the case with lamps used for light. Lamps having heat-resisting glass bulbs or tubular fused quartz envelopes are recommended where liquids might come in contact with the bulb.

The distribution of power radiated by various infrared sources is shown in Figure 6-24. For application information, see Chapter 5, Nonvisual Effects of Optical Radiation.

Low-Voltage Miniature and Sealed Beam Lamps. The term “miniature” applied to light sources is a lamp manufacturer’s designation determined by the trade channels through which these lamps are distributed, rather than by the size or characteristics of the lamps. In general, however, most miniature lamps are small and require relatively little power. The most notable exceptions to this generalization are sealed

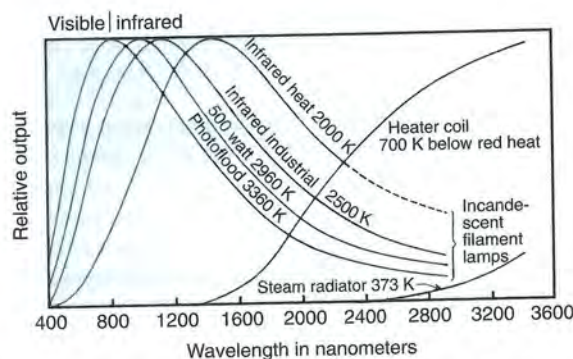


Figure 6-24. Spectral power distribution from various infrared sources.

beam lamps, such as automotive headlamps and aircraft landing lamps, some of which are classed as miniature lamps, even though they can be as large as 200 mm (7.3 in.) in diameter and dissipate up to 1000 W.

The great majority of miniature lamps are either incandescent filament lamps or glow lamps; the latter are discussed under "Miscellaneous Discharge Lamps" later in this chapter. Also, electroluminescent lamps and light-emitting diodes (see sections below) are included in the miniature lamp family. Incandescent miniature lamps²¹ and glow lamps²² are specified completely by numbers standardized and issued by ANSI.

With the notable exception of multiple holiday lamps, miniature incandescent lamps are designed to operate below 50 V. These voltages are often obtained from batteries or generators. These miniature lamps can be operated on 120-V circuits when step-down transformers, series circuits, rectifiers, or resistors are used to reduce the voltage.

Miniature lamps are used chiefly when conditions require a small light source or little power. To insure that the lamp is as small as possible, base sizes are matched to the bulb and the application. They have many uses, principally in automobiles, aircraft, decoration, and as glow lamps in electronic circuits. Both long-life and fleet-service (heavy-duty filaments) products are replacements for standard miniature lamps in the automotive sector. Halogen miniature lamps often are used to replace incandescent miniature lamps. These halogen lamps deliver a whiter and brighter light than the incandescent lamps they replace.

Subminiature lamps have increased in popularity. They range in size from T-2 to T- $\frac{1}{8}$. The T-1- $\frac{3}{4}$ and T-1 are used extensively for instruments and indicators. The T- $\frac{3}{8}$ and smaller sizes down to T- $\frac{1}{8}$ are used chiefly in such novelty applications as tiny flashlights, jewelry, and medical instruments.

Train and Locomotive. Lamps designated for train and locomotive service are designed for several classes of low-voltage (75-V or lower) service. The power usually is provided by generators, with a battery connected in parallel so that both supply power to the lamps. Low-voltage lamps have shorter and heavier filaments than 120-V lamps of the same wattage; consequently, they are more rugged and have higher efficacy.

DC Series. Transit system voltages and some railway shop and yard voltages range from 525 to 625 V. Lamps for such service are operated with five to twenty lamps in series. The design voltages of individual lamps operated five in series are nominally 115, 120, and 125 V. Lamps of the dc series are rated in unusual wattages (36, 56, 94, or 101 W).

Gas-filled 30-V lamps are used for car lighting. The trolley voltage divided by 30 determines the number of lamps connected in series across the line. These lamps are equipped with short-circuiting cutouts that short-circuit the lamps on burnout, thus preventing arcing and leaving the remainder of the lamps in a given circuit operating. These 30-V lamps are rated in amperes, instead of in the usual watts.

Aviation. Lighting for aviation is divided into two classes: lighting on and around airports, and lighting on air-

craft. In airport lighting, both multiple and series type lamps are used. Most systems use series lamps of 6.6- and 20-A designs for airport approach, runway, and taxiway lighting. Multiple lamps are used for obstruction, hazard beacon, and airport identification beacon lighting. On aircraft, small and miniature lamps are used for both interior and exterior lighting. Most lamps used in airport lighting are designed to produce a controlled beam of light complying with required standards from such regulators as the U.S. Federal Aviation Authority (FAA) and Transport Canada.

Hazard beacons and airport identification beacons, signaling the presence of high obstructions or the whereabouts of the airport, use lamps ranging from 500 to 1200 W. Lamps used on the airport proper range from 10 to 500 W. Lamps used for aircraft lighting are in the miniature classification, except for landing lamps, which can be rated as high as 1000 W. See also "Flashtubes," later in this chapter, for alternative beacon sources.

Tungsten-halogen lamps are often provided in place of many regular incandescent types because of their better lumen maintenance and longer life. See Chapter 23, Transportation Lighting, for information on the application of lamps in airports and aircraft lighting.

Indicator and Other Service Lamps. Lamps for indicator, radio, and television service usually are operated from low-voltage transformers.

Flasher Lamps. Incandescent lamps that flash automatically (Figure 6-25), because of a built in bimetal strip similar to those used in thermostats, are available in several sizes. When the lamp lights, heat from the filament causes the bimetal strip to bend away from the lead-in wire. This breaks the circuit and the lamp extinguishes. As the bimetal strip cools, it returns to its original position against the lead-in wire and lights the lamp. This alternating cooling and heating keeps the lamp flashing. An exception to this is found in a certain type of miniature screw base lamps called the shorting type. The bimetal in this type is so mounted that it shorts across the lead-in wire when hot. If these lamps, which are difficult to distinguish from the opening type, are



Figure 6-25. Typical flasher showing bimetal strip.

inserted in sockets intended for the normal flasher lamps, they can drain batteries, blow fuses, overheat wires, or ruin transformers.

Typical Uses. Indicator lamps provide a visual indication of existing circuit conditions. They are widely used in fire and police signaling systems, power plant switchboards, production machinery, motor switches, furnaces, and other devices requiring warning or pilot lights.

Indicator lamps can be wired with motor or heating elements and can be used to indicate that the current is flowing to an appliance or that it is functioning properly. They often are used in other instrumentation and with photocells and relays. Flashlights, radios, clocks, bicycles, and toys account for more uses. Other applications include the use of miniature lamps for holiday and other festive occasions, and for colorful patio and garden lighting. For garden lighting, low-voltage miniature equipment is available.

Flashlight, Handlantern, and Bicycle. These lamps are commonly operated by dry-cell batteries having an open-circuit voltage of 1.5 V per cell for new batteries, dropping to approximately 0.9 V per cell at the end of battery life. This voltage drop results in a reduction in light output in a manner analogous to that shown in Figure 6-19a.

Automotive. Lamps for most passenger vehicles, trucks, and coaches operate at 12 V. The power source is a storage battery-rectified alternator system. Head lamps include sealed beam and halogen capsules.

SEALED BEAM AND TUNGSTEN-HALOGEN EPOXY SEALED BEAM LAMPS. These lamps contain filaments, lens, and reflectors in a precise, rugged optical package available in a wide variety of sizes and voltages ranging from 6 to 28 V. Sealed beam lamp lenses are made of borosilicate "hard" glass. The reflector is vaporized aluminum on glass and in the incandescent versions is hermetically sealed to the lens cover. The advantages are accurate reflector contour for accurate beam control, precise filament positioning on rugged filament supports, and high efficacy and excellent lumen maintenance. Vaporized aluminum on glass is an excellent reflector, it does not deteriorate, and the normal bulb blackening has little effect on output throughout lamp life. The sealed beam lamp is particularly suitable where a large amount of concentrated light at low voltage is required, as with automotive head lamps. Tungsten-halogen epoxy-sealed beam lamps contain a small bulb of aluminosilicate glass, surrounding the filament. The bulb also contains a high-pressure, rare-gas atmosphere with small additions of halogen compounds as required for operation of the tungsten-halogen cycle.

REPLACEABLE AUTOMOTIVE HALOGEN HEAD LAMPS. Changes in automotive styling have led to the creation of replaceable halogen capsules. These lamps meet the current Society for Automotive Engineers (SAE) standards while allowing the designer to use additional shapes of head lamps. Special automotive bases have the advantage that only the light source, rather than the entire assembly, can be replaced when necessary.

Sealed beam lamps are made in a number of rectangular and round versions to allow for automotive design flexibility. They are also available in both single and dual filament designs.

Photo-optical and photographic applications

Photo-Optical Lamps. Lamps designed specifically for photo-optical applications typically require tighter tolerances on the positioning of the filament and very often have special pefocus bases to ensure proper alignment in application. In the typical photo-optical application, the prime objective is to collect and direct the lamp's output through an aperture or film gate. In some applications, such as video projection and fiber-optic illuminators, collimation of the light is also needed. In many cases low-voltage filaments are used to provide the smallest but highest luminance source possible, resulting in the greatest optical efficiency. Life is often sacrificed for efficacy and source flex. Typical applications are film, slide, overhead, and video projection, microfilm viewers, and microscope and fiber-optic illuminators.

Tungsten-halogen lamps have nearly replaced conventional incandescent lamps for most photo-optical applications. Their small size allows for more efficient optical control. See "Tungsten-Halogen Lamps" earlier in this chapter for additional information.

One of the principal developments has been the adoption of halogen lamp types with integrated external dichroic mirrors. By carefully positioning the lamp filament in ellipsoidal or parabolic dichroic reflectors, good beam control is possible. This obviates bulky and expensive external condensers and reflectors. The dichroic mirror is constructed to transmit most of the infrared radiation and reflect light through the film plane. This results in a lower film gate temperature or aperture temperature leading to longer film and optical component life.

Photographic. Lamps used specifically for photographic service are adapted to the response or sensitivity of several classes of film emulsions. Some lamps are specified in terms of color temperature, which serves as a basic rating for film exposure data. Lamp life is less important. Lamps of various size often are matched for color temperature, and rated life varies as necessary with wattage to achieve the specified color temperature. Typical color temperature-rated lamps of conventional construction can drop by 100 K throughout life. There is negligible change in the color temperature of tungsten-halogen lamps during their life.

Photoflood. These are high-efficacy sources similar to other incandescent filament lamps for picture taking, with color temperatures ranging from 3200 to 3400 K. Because of their high filament temperature, these lamps generally produce approximately twice the luminous flux and three times the photographic effectiveness of similar wattages of general-service lamps. Relatively small bulb sizes are employed. The 250-W No. 1 photoflood, for example, is the same size as the 60-W general-service lamp. These lamps can be con-

veniently used in less bulky reflecting equipment or for certain effects in ordinary residential or commercial luminaires.

The photoflood family includes reflector and projector (PAR) lamps with various beam spreads. Some of these have tungsten-halogen sources; some have integral 5000-K daylight filters. In addition, tungsten-halogen lamps in several sizes and color temperatures are classed as photofloods and used in specially designed reflectors.

FLUORESCENT LAMPS

The fluorescent lamp is a low-pressure gas discharge source, in which light is produced predominantly by fluorescent powders activated by UV energy generated by a mercury arc. The lamp, usually in the form of a long tubular bulb with an electrode sealed into each end, contains mercury vapor at low pressure with a small amount of inert gas for starting. The inner walls of the bulb are coated with fluorescent powders commonly called phosphors. When the proper voltage is applied, an arc is produced by current flowing between the electrodes through the mercury vapor. This discharge generates some visible radiation, but mostly invisible UV radiation, the principal lines being approximately 254, 313, 365, 405, 436, 546, and 578 nm. The UV in turn excites the phosphors to emit light. The phosphors are generally selected and blended to respond most efficiently to 254 nm,^{23,24} the primary wavelength generated in a mercury low-pressure discharge. See Figure 6-26 and the discussion of fluorescence in Chapter 1, Light and Optics.

Like most gas discharge lamps, fluorescent lamps must be operated in series with a current-limiting device. This auxiliary, commonly called a ballast, limits the current to the value for which each lamp is designed. It also provides the required starting and operating lamp voltages and may provide dimming control.

Lamp Construction

Bulbs. Linear fluorescent lamps are commonly made with straight, tubular bulbs varying in diameter from approximately 6 mm (0.25 in. T-2) to 54 mm. (2.125 in. T-17) and in overall length from a nominal 100 to 2440 mm (4 to 96 in.). The bulb is historically designated by a letter indicating the shape, followed by a number indicating the maximum diameter in eighths of an inch. Hence T-8 indicates a tubular bulb 8/8 in., or 1 in. (26 mm), in diameter. The nominal length of the lamp includes the thickness of the standard lampholders and is the back-to-back dimension of the lampholders with a seated lamp.

Fluorescent lamps also come in shapes other than straight tubes. U-shaped tubes are formed by bending tubes in half. They are commonly used in 0.61 m (2 ft) square luminaires. Circular (circline) lamps are tubes bent in a circle with the two ends adjacent to each other. In increasing use are smaller diameter, single-ended, compact fluorescent lamps

consisting of multiple shaped tubes joined together to form a continuous arc path (Figure 6-26). They are designed to approach the size of the incandescent lamp.

Commonly used lamp designations are shown in Figure 6-27. The 32 W T-8 lamp is used as an example, but the designations for most fluorescent lamps follow the same principles.

Nomenclature of Fluorescent Lamps. Fluorescent lamps can be designated as illustrated in Figure 6-27. This is only one example; often manufacturers will adopt variations. The specifier should consult with the manufacturer to ensure correct nomenclature for design purposes.

Electrodes. Two electrodes are hermetically sealed into the bulb, one at each end. These electrodes are designed for operation as either cold or hot cathodes, more correctly called glow or arc modes of discharge operation.

Electrodes for glow (cold cathode) operation can consist of closed-end metal cylinders, generally coated on the inside with an emissive material. Cold cathode lamps operate at a few hundred milliamperes, with a high value of the cathode fall (the voltage required to create ion and electron current flow) in excess of 50 V.

The arc mode (hot cathode) electrode generally is constructed from a single tungsten wire, or a tungsten wire around which another very fine tungsten wire has been uniformly wound. The larger tungsten wire is coiled, producing a triple-coil electrode. When the fine wire is absent, the electrode is referred to as a coiled-coil electrode. The coiled-coil or triple-coil tungsten wire is coated with a mixture of alkaline earth oxides to enhance electron emission. During lamp operation, the coil and coating reach temperatures of approximately 1100°C (2012°F), at which point the coil-and-coating combination thermally emits large quantities of electrons at a low cathode fall, in the range of 10 to 12 V. The normal operating current of arc mode lamps is approximately 1.5 A or less. As a consequence of the lower cathode fall associated with the hot cathode, more efficient lamp operation is obtained, and therefore most fluorescent lamps are designed for such operation.

Gas Fill. The operation of the fluorescent lamp depends on the development of a discharge between the two electrodes sealed at the extremities of the lamp bulb. This discharge is developed by ionization of mercury gas contained in the bulb. The mercury gas is typically maintained at a pressure of approximately 1.07 Pa (0.00016 lb/in.²), which is the vapor pressure of liquid mercury at 40°C (104°F), the optimum bulb wall temperature of operation for which most lamps are designed (see the section "Temperature Effect on Operation" below). In addition to the mercury, a rare gas or a combination of gases at low pressure, from 100 to 400 Pascals (0.015 to 0.058 lb/in.²), is added to the lamp to facilitate ignition of the discharge. Standard lamps employ argon gas; energy-saving types, a mixture of krypton and argon; others, a combination of neon and argon or of neon, xenon, and argon.

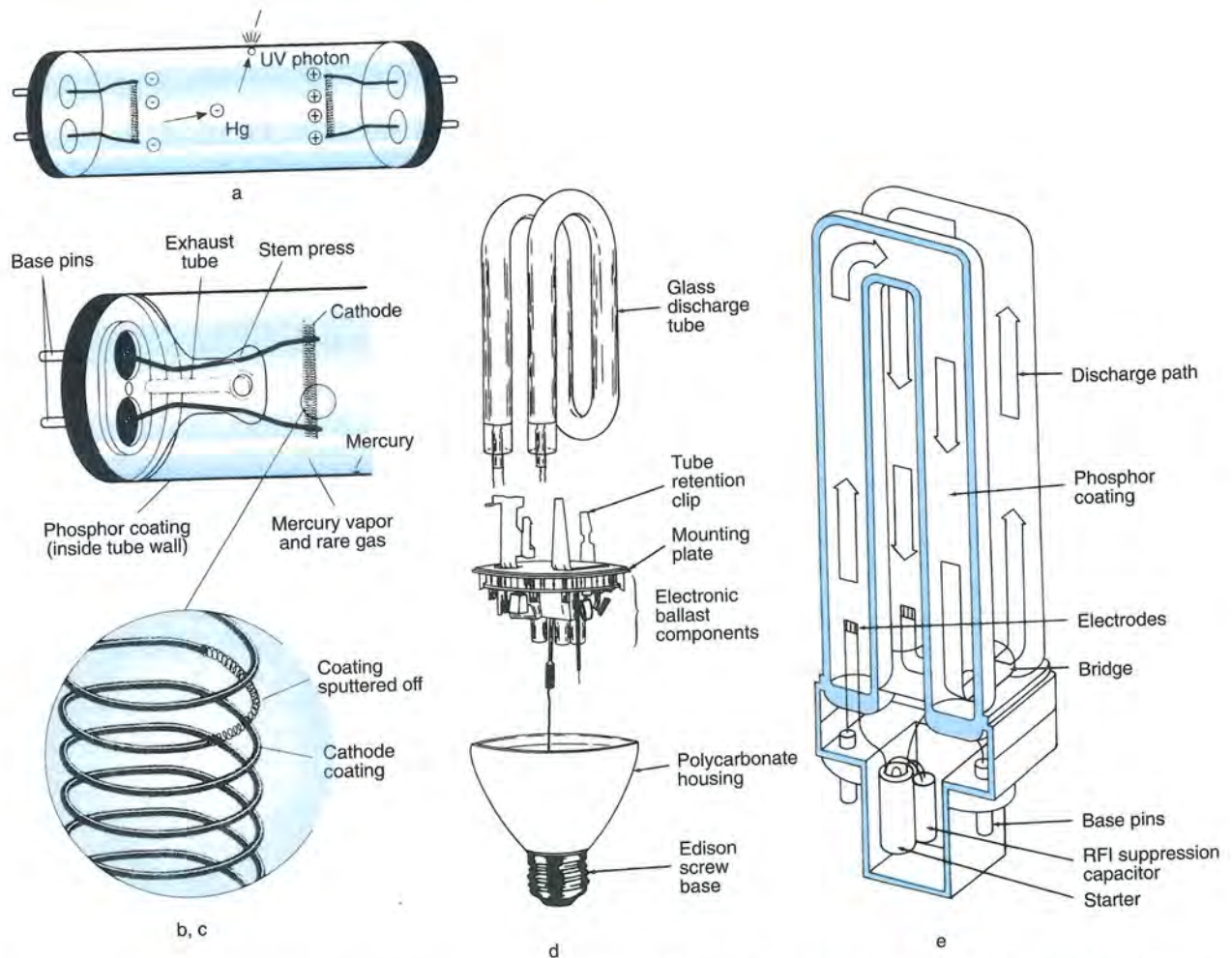


Figure 6-26. Cutaway view of some common fluorescent lamps: (a) A typical rapid-start fluorescent lamp and the production of light; (b) lamp electrode construction; (c) detail of the electrode; (d) a screw-in compact fluorescent lamp with built-in ballast; (e) a 2-pin plug-in compact fluorescent lamp with built-in starter.

Figure 6-27. Nomenclature of Fluorescent Lamps

F	32	T8	RE735	/ES/HO
(a)	(b)	(c)	(d)	(e)
(a) Lamp type. "F" is used for fluorescent lamps. "FB" or "FU" is used for U-bent lamps, while "FT" is used for twin-tube lamps. (b) Wattage for preheat and rapid start lamps; or lamp length (in.) for slimline and HO lamps. (c) Diameter of tube (in eighths of an inch). "T8" is a 1-in. diameter tube, and "T12" is a 1.5-in. diameter tube. (d) Lamp color (sometimes omitted). "RE" indicates a rare earth phosphor; "7" represents the first digit of the CRI (between 70 and 79); "35" represents the first two digits of the CCT (between 3500 and 3599). For halophosphate lamps, the color might be represented as in these examples: "CW" for cool white or "WW" for warm white. (e) Optional modifiers. "ES" represents an energy saving lamp; "HO" is high output; "VHO" is very high output. These are often preceded with a slash ("/").				

Phosphors. The color of the light produced by a fluorescent lamp depends on the blend of phosphors used to coat the wall of the tube (see Figure 1-12 for a list of important phosphors). Many different white and colored fluorescent lamps are available, each having its own characteristic spectral power distribution (Figure 6-28). These types have a combination of continuous and line spectra.

Popular fluorescent lamps use three highly efficient narrow-band, rare-earth activated phosphors with emission peaks in the short-, middle-, and long-wavelength regions of the visible spectrum. These triphosphor lamps can be obtained with high color rendering, improved lumen maintenance, and good efficacy with correlated color temperatures between 2500 and 6000 K relative to halophosphate lamps.^{25,26}

Since the rare-earth phosphors are expensive, the longer T-5, T-8, T-10, and T-12 triphosphor lamps typically employ a two-coat system consisting of a less expensive halophos-

phate phosphor applied with the rare-earth type. The rare-earth activated phosphor is closest to the mercury discharge and, as a result, the spectral power distribution of the lamp is more influenced by these phosphors. Common commercial types have correlated color temperatures of 3000, 3500, and 4100 K.

A variety of lamp types is available that radiate in particular wavelength regions for specific purposes, such as plant growth, merchandise enhancement, and medical therapy.

Various colored lamps, such as blue, green, and gold, are obtained by phosphor selection and filtration through pigments.

Bases. For satisfactory performance, a fluorescent lamp must be connected to a ballasted electrical circuit with proper voltage and current characteristics for its type. Several fluorescent lamp base designs are used. The bases physically support the lamp in most cases and provide a means of electrical connection (Figure 6-26).

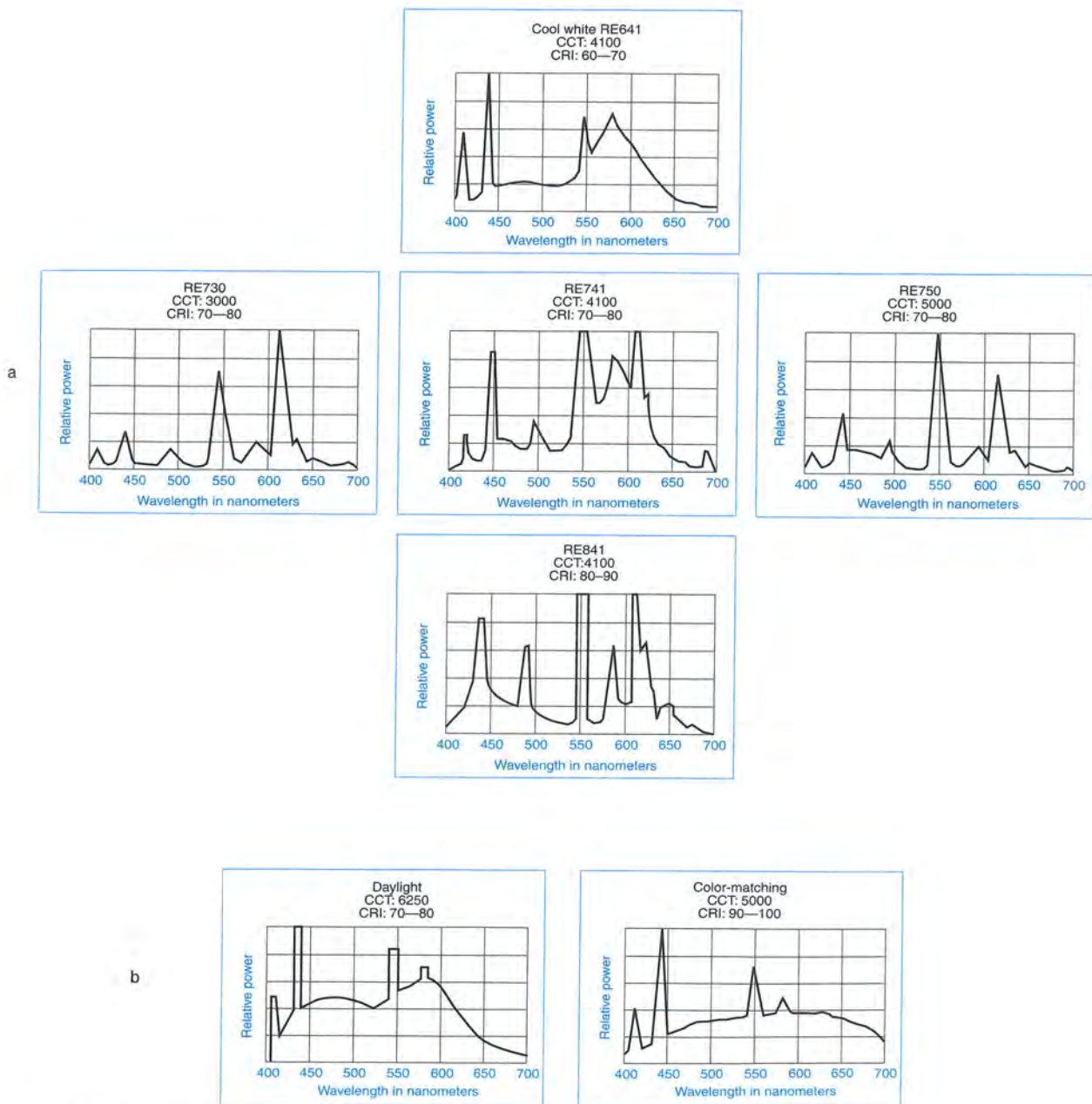


Figure 6-28a and b. Approximate spectral power distribution charts for various types of fluorescent lamps.

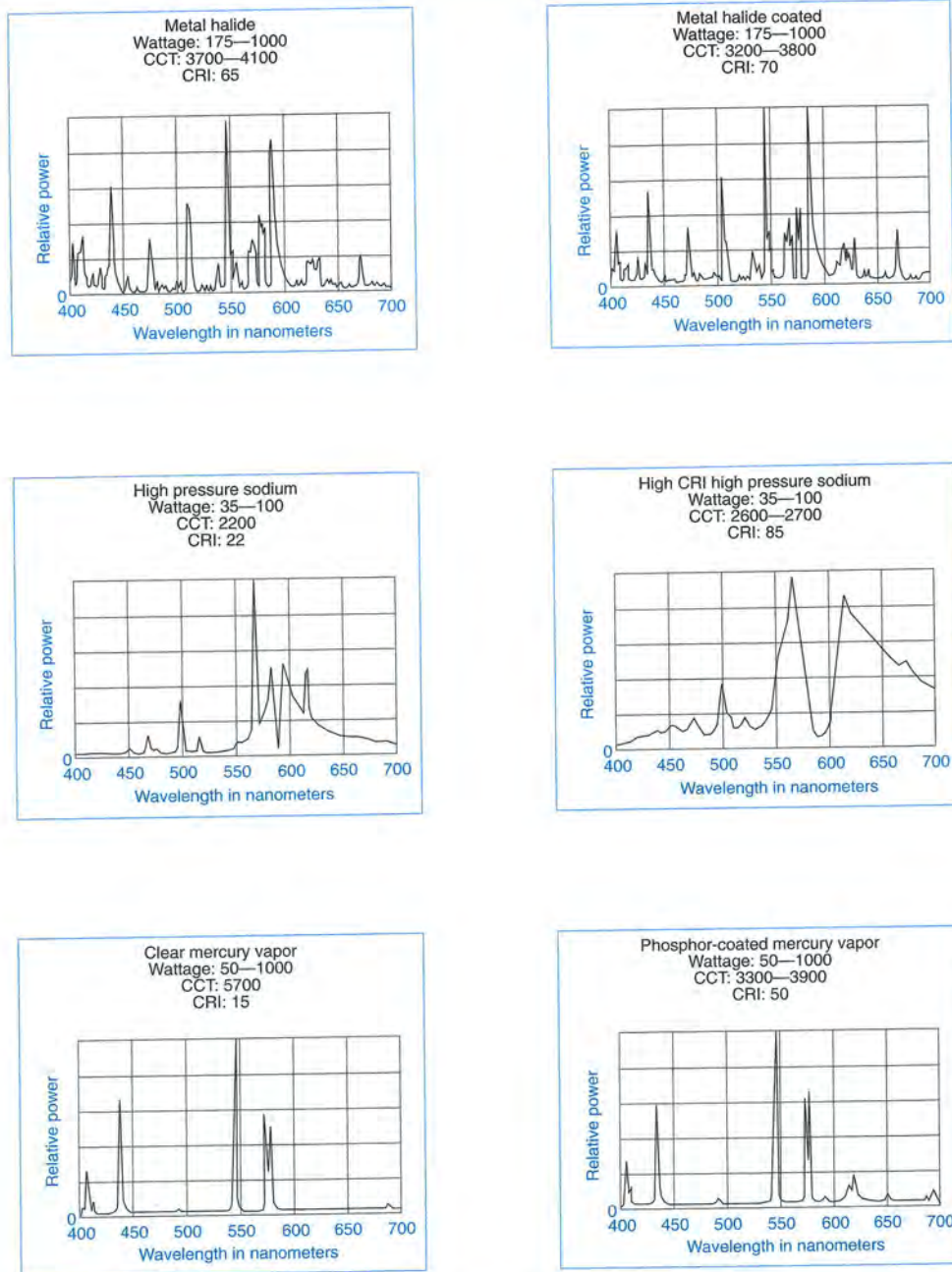


Figure 6-28c. Approximate spectral power distribution charts for various types of HID lamps.

Straight tube lamps designed for instant-start operation (see the section “Instant-Start Lamp and Ballast Operation” below) generally have a single connection at each end. As a consequence, a single-pin base is satisfactory.

Preheat and rapid-start lamps (see the section “Lamp Starting” below) have four electrical connections, two at each end of the tube, and therefore require dual-contact bases. In the case of the circline lamp, a single four-pin connector is re-

quired. Many compact fluorescent lamp bases have unique designs to help ensure their use with the correct ballast.

Single-ended compact fluorescent lamps with integral starters have plastic bases containing a glow switch and a noise reduction filter capacitor. These bases have two connection pins. Some lamp wattages are available without the starting components mounted within the bases and have four connection pins (Figure 6-29). Only four-pin lamps are dim-



Figure 6-29. Typical bases for linear and compact fluorescent lamps (not to scale). ANSI designations are shown.

mable. For incandescent lamp retrofit applications, self-ballasted compact fluorescent lamps have medium screw bases.

Common Fluorescent Lamp Families

T-12 Fluorescent Lamps. Until the National Energy Policy Act of 1992 (EPACT), the most commonly applied fluo-

rescent lamp in the United States and Canada was the T-12, 40-W, 4-ft (1.22-m), rapid-start lamp with a cool white or warm white phosphor. EPACT banned the production of these type lamps after 1995. EPACT also impacted the T-12, 8-ft (2.44 m) lamps. As with 4-ft lamps, only reduced wattage or improved color rendition lamps are currently

duced for U.S. consumption. For many new installations, the more efficient T-8 lamps are often specified.

Legislation similar to EPACT exists in Canada, where energy efficiency standards for fluorescent lamp ballasts, fluorescent lamps, and incandescent reflector lamps have been established under the Energy Efficiency Act. Regulated products cannot be imported into Canada or traded between its provinces unless they meet the regulatory requirements.

Energy-Saving Fluorescent Lamps. In response to the energy crisis of the 1970s, lamp companies introduced halophosphate T-12 lamps filled with an argon-krypton gas mixture, rather than argon only. The 4-ft (1.22 m) lamps can be operated suitably on a ballast designed for 4-ft (1.22 m) 40-W lamps, but because of the different gas mixture they dissipate approximately 34 W per lamp. Any of the energy-saving ballasts that operate standard lamps at full light output can be used, provided the ballast is listed for use with the lamps; this information is stated on the ballast label. These lamps may not be used with any ballast that provides reduced wattage and thus reduced light output in a standard lamp, nor with any ballast that does not list the lamp on its label. A transparent conductive coating is applied to these energy-saving lamps, resulting in a lower required starting voltage and less lumen output. By using these lamps as a retrofit in overilluminated spaces, a saving of 5 to 6 W per lamp can be achieved.

Whether operated on standard or energy-efficient magnetic ballasts, energy-saving fluorescent lamps generate approximately 87% of the light generated by a standard (40-W T-12) lamp at 25°C (77°F). This lamp-ballast system is less efficient than the standard argon gas lamp-ballast system, since it generates fewer lumens per watt. This is due to increased ballast losses. In addition, these lamps cannot be dimmed as easily as standard T-12 lamps, and they are more sensitive to temperature, especially in regard to starting, and should not be started or operated at low temperatures.

T-8 Fluorescent Lamps.^{27,28} T-8 fluorescent lamps are a family of 1-in.-diameter (25.4 mm) straight tube lamps manufactured in some of the same lengths as T-12 lamps. The 4-ft version of the lamp is designed to consume approximately 32 W. It is also available in 2-, 3-, 5- and 8-ft. (0.16-, 0.91-, 1.52-, and 2.44-m) lengths. The smaller diameter makes it economical to use the more efficient and more expensive rare-earth phosphors. Although the T-8 and T-12 lamps are physically interchangeable, they cannot operate on the same ballast. T-8 lamps are designed to operate on line-frequency rapid-start ballasting systems at approximately 265 mA, or on high-frequency electronic ballasts at slightly less current. Due to the higher efficacies that can be reached with T-8 systems, they have replaced the conventional T-12 lamps in many applications.

T-5 Fluorescent Lamps. T-5 fluorescent lamps are a family of smaller diameter straight tube lamps employing triphosphor technology. Available only in metric lengths and mini bipin bases, the T-5 lamps provide a higher source

brightness than T-8 lamps and better optical control. The lamps provide optimum light output at an ambient temperature of 35°C (95°F) rather than the more typical 25°C (77°F), allowing for the design of more compact luminaires. Also available are high-output versions providing approximately twice the lumens at the same length as the standard versions. T-5 lamps are designed to operate solely on electronic ballasts. Their unique lengths, special lampholder, and ballast requirements make them unsuitable for most retrofit applications. These lamps are used in shallower luminaires than the T-8 lamps, which are more efficient over all than luminaires for T-8 lamps.

Compact Fluorescent Lamps. The rare-earth activated phosphor has led to the development of a growing variety of multitube or multibend single-ended lamps known as compact fluorescent lamps (CFLs). The lamps originally were designed to be interchangeable with conventional 25- to 100-W incandescent lamps, but now this lamp type includes sizes that replace conventional fluorescent lamps in smaller luminaires.

T-4 and T-5 tubes typically are used in compact fluorescent lamps. There are many techniques of adding, bending, and connecting the tubes to obtain the physical size and lumen output desired. The tube portion of the lamp is sometimes enclosed in a cylindrical or spherical outer translucent jacket made of glass or plastic. Some lamps contain the lamp starter, while others contain both the starter and the ballast, which can take the form of a simple magnetic choke or an electronic ballast.

Present compact lamp wattages vary from 5 to 55 W, and rated lumen output ranges from 250 to 4800 lm. Overall lamp length varies from 100 to 570 mm (3.93 to 22.4 in.), depending on lamp wattage and construction. Some designs with self-contained ballasts are equipped with Edison-type screw-in bases for use in incandescent sockets (Figure 6-26d), while other designs use special pin-type bases for dedicated use with mating sockets designed for lamps of a particular wattage (Figure 6-26e). Because of the high power density in these lamps, high-performance phosphors are used extensively in order to enhance brightness, lumen maintenance, and color rendering ability. Amalgams can be added to some versions to enhance performance under a range of operating temperatures.

Special Fluorescent Lamps: Subminiature, Reflector, Cold Cathode, and Electrodeless. In addition to the lamps described above, four families of fluorescent lamps are designed and constructed for special applications: subminiature, reflector, cold cathode fluorescent, and electrodeless fluorescent lamps.

Subminiature fluorescent lamps are extremely small. They were first used in the backlighting of liquid crystal displays. They are two basic types: hot cathode and cold cathode. The lamps all have bulb diameters of 7 mm (approximately T-2- $\frac{1}{2}$).

The cold cathode series ranges from 1 to 3 W, having an output of 15 to 130 lm, respectively. Standard lamp lengths

range from 10 to 50 mm (0.4 to 2.0 in.). These low-power light sources have a low bulb wall temperature, which is important when backlighting displays where space is limited and components must be kept cool. The lamps have a rated life of 20,000 h.

The hot cathode family of subminiature fluorescent lamps ranges from 4 to 13 W, with lumen output packages ranging from 95 to 860 lm, respectively. The lumen output is similar to T-5 preheat fluorescent lamps of comparable length. The hot cathode lamps have a rated life of 10,000 h. Their high light output lends them to such general lighting applications as display lighting, valance lighting, furniture-mounted task lighting, and other applications requiring small-diameter, linear light sources.

The triphosphor blends in both hot and cold cathode products provide for improved efficacy at the higher wattages and good color rendering (CRI of about 80).

Reflector fluorescent lamps are designed for applications requiring directional light output distribution patterns. They have a white powder reflective layer between the phosphor and the bulb that covers a major angular portion of the envelope wall. The major portion of the light is emitted through the strip coated with just the fluorescent phosphor. A cross-sectional diagram and a relative candlepower distribution for a 235° reflector lamp are shown in Figure 6-30. Reflector lamps with other angular widths are available. As a consequence of the reflector layer, absorption of generated light is somewhat higher than in standard fluorescent lamps, producing a somewhat reduced total light output.

Cold cathode fluorescent lamps often are used in decorative, sign lighting, and other architectural applications. Due to their high energy losses associated with electrode operation, they are not as efficacious as the more widespread hot cathode lamps for lengths up to 2.44 m (8 ft). The lamps can be custom manufactured in special shapes and sizes. They are frequently manufactured with small diameter tubing so they can be bent into various shapes and sizes. Cold cathode lamps with color phosphors can replace neon tubes in many applications where exposed sources are acceptable. Other advantages of cold cathode lamps include immediate starting, even under cold conditions, and long life unaffected by the number of starts.

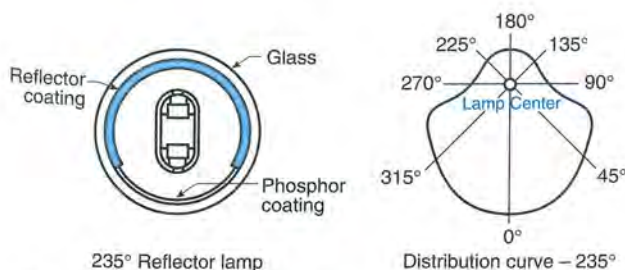


Figure 6-30. Cross-section diagrams and relative candlepower distribution curves for 235-degree reflector lamp.

Neon lamps are cold cathode lamps lacking a phosphor coating. The color of the nonfluorescent neon lamps is determined primarily by the fill gas. Neon emits red, whereas argon mixed with mercury vapor emits blue. Combined with colored glass, these and other gas fills create additional colors.

Other special lamps are available for extreme ambient temperatures. One family, designed for low temperatures, incorporates a jacket to conserve heat. Another, for high temperatures, incorporates a mercury amalgam. In both cases, these lamps are designed to optimize the mercury vapor pressures at unusual temperatures.

Electrodeless Lamps. Electrodeless lamps have begun to appear on the general lighting market because of advances in the electronics industry and changes in electromagnetic interference (EMI) standards over the last 30 years.

Electrodeless lamps use an electromagnetic (EM) field, instead of an electric current passing through electrodes, to excite the gas in a bulb. Electrodeless lamps can be categorized according to the method by which they produce EM fields: either inductive discharge or microwave discharge.

Inductive discharge lamps (Figure 6-31), also known as induction lamps, operate using the principle of induction. These lamps also are called electrodeless fluorescent lamps because their EM fields produce light by exciting the same phosphors found in conventional fluorescent lamps. They operate as follows:

1. The radio frequency (RF) power supply sends an electric current to an induction coil (a wire wrapped around a plastic or metal core).
2. The current passing through the induction coil generates an EM field.
3. The EM field excites the mercury in the gas fill, causing the mercury to emit ultraviolet (UV) energy.
4. The UV energy strikes and excites the phosphor coating on the inside of the glass bulb, producing light.

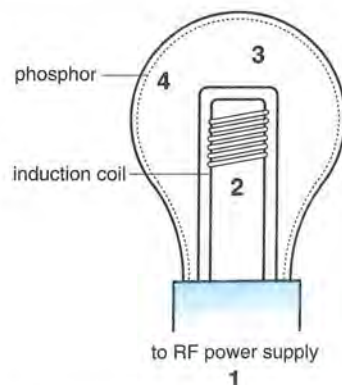


Figure 6-31. Diagram of an induction lamp.

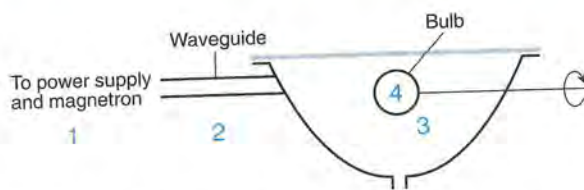


Figure 6-32. Operation of the microwave discharge lamp.

Microwave discharge lamps (Figure 6-32) generate microwaves, which excite the plasma. They operate as follows:

1. A magnetron generates a microwave field.
2. The microwaves travel through a waveguide into a cavity.
3. In the cavity, a hollow glass or quartz ball rotates at high speed to stabilize the fill in the ball (necessary for a uniform light distribution).
4. The excited fill forms a plasma that emits light.

The efficacies of electrodeless lamps are like those of CFLs or HID lamps of comparable light output. Electrodeless lamps use rare-earth phosphors, giving them color properties similar to those of higher-end fluorescent lamps.

Electrodeless lamps are electronic devices, and like all electronic devices they generate EM waves. Electromagnetic interference (EMI) occurs when unwanted EM signals, which can travel through wiring or radiate through the air, interfere with desirable signals from other devices. In the United States, the Federal Communications Commission (FCC) regulates EM emissions in the communication frequencies of 450 kHz to over 960 MHz. Canada also regulates EM emissions over these frequencies through Industry Canada. Manufacturers must comply with FCC regulations to sell products in the United States. However, manufacturer compliance does not assure that EMI will not occur in unregulated frequencies. The International Special Committee on Radio Interference develops standards for EMI from lighting devices, which are accepted by the European community.

Of the available induction lamps, one operates at 13.56 MHz and meets FCC requirements without shielding. It is approved for both commercial and residential use. Others operate at 2.65 MHz, which meets the European community's standard for induction lighting. Sometimes, appropriate luminaires must be used to meet shielding requirements; some lamps meet the FCC's EMI requirements for commercial use but not for residential use because their reflectors offer some shielding. Figure 6-33 gives the performance

Figure 6-33. Performance Characteristics of Typical Electrodeless Lamps

	Electrodeless Discharge		Others, for comparison		
	Induction	Microwave	Incandescent R30	Self-ballasted CFL	Metal Halide
Input power (watts)	23–85	3400/5900*	75	25	70/89*
Restrike time (minutes)	< 1 s	< 1 s	instant	instant	15
Minimum starting temperature (°F)	– 4 to 32	NS	none	0	– 22
Power factor (watts/volt-ampere)	> 0.90	> 0.90	1	> 0.95	0.85
Total harmonic distortion (%)	< 10	NS	0	< 20	NS
Correlated color temperature (K)	2700–4000	4000–9000	2800	2700	3200
Color rendering index	> 80	> 80	> 95	82	75
Initial light output (lumens)	1100–6000	450,000	900	1520	5200
Efficacy (lumens/watt)*	48–70	76*	12	61	58*
Average rated life (hours)	10,000–100,000	10,000–20,000	2000	10,000	10,000–15,000*

The data reported was supplied by manufacturers.

NS = not supplied

* Lamp power/lamp and ballast power.

* Efficacy includes ballast power.

* Life depends on burn position.

* This is not system efficacy.

characteristics of typical electrodeless lamps in comparison to other lamps.

The microwave lamp operates at 2.45 GHz for regulatory and economic reasons. That frequency is approved for consumer electronics; for example, microwave ovens operate at 2.45 GHz. Because of the popularity of the microwave ovens, magnetron parts are produced in large quantities and are relatively inexpensive.

Performance Parameters

Figure 6-3 lists several performance parameters for many common fluorescent lamps. These parameters are discussed in more detail below.

Luminous Efficacy: Light Output. Three main energy conversions occur in a fluorescent lamp. Initially, electrical energy is converted into kinetic energy by accelerating charged particles. These in turn yield their energy during particle collision to electromagnetic radiation, particularly UV. This UV energy in turn is converted to visible energy by the lamp phosphor. During each conversion some energy is lost, so that only a small percentage of the input is converted into visible radiation. Figure 6-34 shows the approximate energy distribution in a typical cool white fluorescent lamp.

The geometric design and operating conditions of a lamp influence its efficacy. Figures 6-35 and 6-36 show the effect of the bulb design on lamp operation. Figure 6-35 shows that at a constant current, as the lamp diameter increases, the efficacy increases, reaches a maximum, and then decreases.²⁹ The reasons for this phenomenon are two-fold. In lamps of small diameter, an excessive amount of energy is lost by recombination of electrons with ions at the bulb wall. As the bulb diameter is increased, this loss decreases, but losses due to imprisonment of radiation become correspondingly larger.

As shown in Figure 6-36, the length of a lamp also influ-

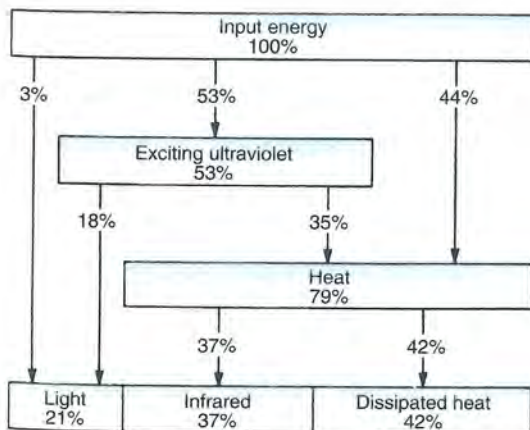


Figure 6-34. Energy distribution in a typical cool white fluorescent lamp.

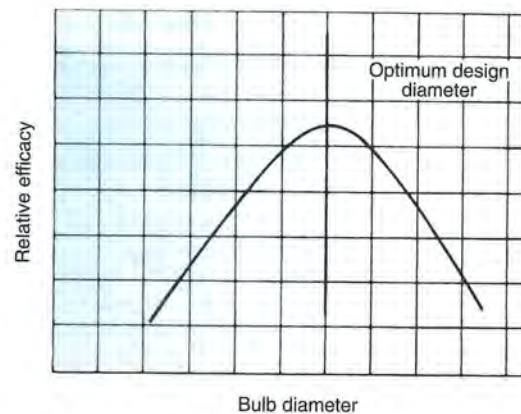


Figure 6-35. Efficacy of typical fluorescent lamps as a function of bulb diameter, holding gas fill pressure with arc current constant.

ences its efficacy; the greater the length, the higher the efficacy. This is based on two separate energy losses within the lamp: the energy absorbed by the electrodes, which do not generate any appreciable light, and the energy losses directly associated with the generation of light. The electrode losses are essentially constant, whereas the loss associated with light generation depends on lamp length. As lamp length increases, electrode loss decreases relative to the total losses.

The operating voltage of a lamp, like its efficacy, is a function of its length, as shown in Figure 6-37. The characteristic electrode voltage drops for the hot and cold cathode T-8 lamps are indicated by the intersection of the curves with the ordinate corresponding to zero arc length.³⁰

Lamp Life. The lamp life of hot cathode lamps is determined by the rate of loss of the emissive coating on the elec-

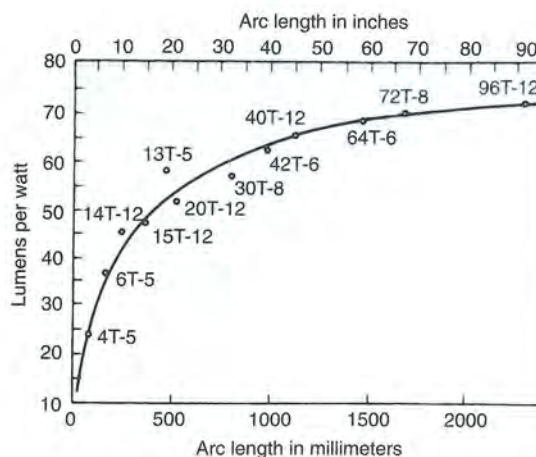


Figure 6-36. Efficacy of a typical halophosphate fluorescent lamp as a function of lamp length.

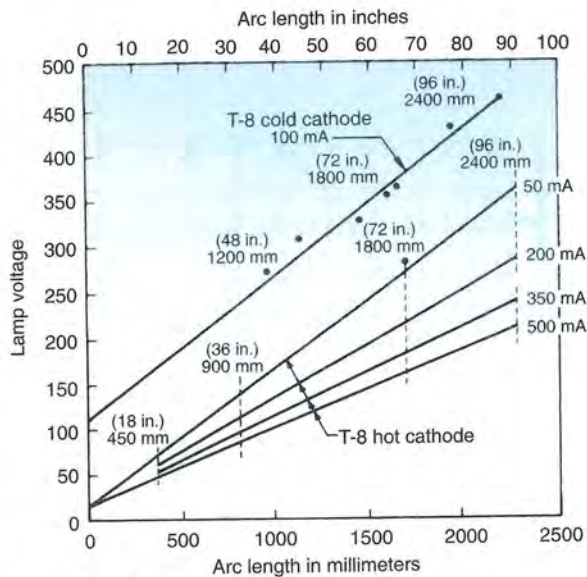


Figure 6-37. Operating voltage of typical hot and cold-cathode 26-mm (T-8) fluorescent lamps as a function of arc length.

trodes (Figures 6-26b and c). Some of the coating is eroded from the filaments each time the lamp is started. Emissive coating also is lost by evaporation during normal lamp operation. Electrodes are designed to minimize both of these effects. The end of lamp life is reached when either the coating is completely removed from one or both electrodes, or the remaining coating becomes nonemissive.

Because some of the emissive coating is lost from the electrodes during each start, the frequency of starting hot cathode lamps influences lamp life. The rated average life of fluorescent lamps usually is based on three hours of operation per start (3 h/start). The estimated effect of burning cycles on lamp life normalized to 100% at 3 h/start is presented in Figure 6-38. Cold cathode lamps are not appreciably affected by starting frequency because of the type of electrode used.

Some electronic ballasts have been designed to instant start rapid-start T-8 and T-12 lamps. Typically there is a 25% reduction in lamp life based upon 3 h/start. Many other conditions affect lamp life. Ballast characteristics and starter design are key factors for preheat circuits. Ballasts that neither provide specified starting requirements nor operate lamps at proper voltage levels can greatly affect lamp life. For preheat circuits, starters also must be designed to meet specified characteristics.

The electrode heating current in rapid-start lamps is critical and is affected not only by ballasts but also by poor lamp-to-lampholder contact or improper circuit wiring. Improper seating of a lamp in a lampholder can prevent electrode heating. Lamps operating in this mode typically fail within 50 to 500 h. Another factor in lamp life is line volt-

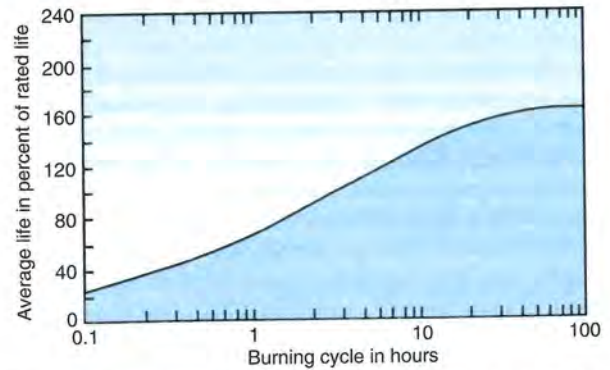


Figure 6-38. Effect of burning cycles on average lamp life for most popular types of rapid-start fluorescent lamps. All fluorescent lamps follow similar functions depending on the specific lamp and ballast used.

age. If the line voltage is too high, it can cause instant starting of lamps in preheat and rapid-start circuits. If it is low, slow starting of rapid-start or instant-start lamps, or the recycling of starters in preheat circuits, can result. All of these conditions adversely affect lamp life. A typical mortality curve for a large group of fluorescent lamps is given in Figure 6-39. This curve has recently been validated, on a first order basis, for rapid-cycle switching.

Ballasts are available for low-temperature starting of rapid-start lamps. At higher temperatures, lamps operating on these ballasts will start before the electrodes are properly heated, shortening lamp life. Time delay relays are available to ensure proper electrode heating prior to application of ignition voltage to the lamp.

R_h/R_c ratio is correlated with fluorescent lamp life for rapid-start electronic ballasts. R_c is the cold lamp electrode resistance at room temperature (25°C [77°F]). R_h is the hot lamp electrode resistance at the end of the preheat period but before the glow to arc transition. The average electrode tem-

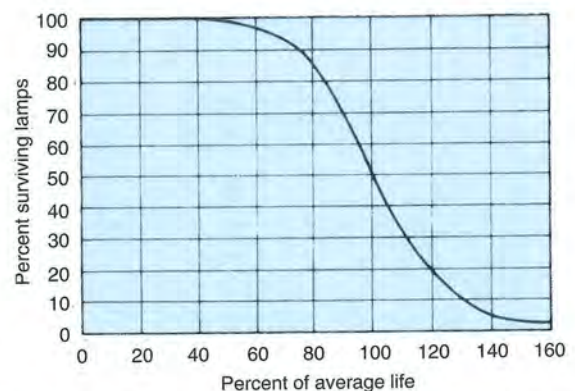


Figure 6-39. Typical mortality curve for a statistically large group of fluorescent lamps (at 3 operating hours per start).

perature before the lamp glow to arc transition (T_h) can be calculated using the equation

$$T_h = T_c \times (R_h/R_c)^{0.814}$$

where T_c is 25°C. This equation is based on the resistance-temperature relationship for tungsten wire. Lamp manufacturers recommend that approximately 700°C is needed to assure minimum sputtering during lamp starting. This electrode temperature correlates to an R_h/R_c ratio of approximately 4.25. For values less than 4.25, sputtering increases and lamp life decreases.

In summary, the R_h/R_c ratio appears to be correlated with lamp life based on lamp starting. A low R_h/R_c ratio indicates that the lamp electrodes have not been heated sufficiently during lamp starting, resulting in reduced lamp life. The data shown here support previous recommendations that for rapid-start electronic ballasts, the R_h/R_c ratio should be equal to or higher than 4.25, representing an average electrode temperature of 700°C.

Lumen Depreciation. The light output of fluorescent lamps decreases with accumulated operating time because of photochemical degradation of the phosphor coating and glass tube and the accumulation of light-absorbing deposits within the lamp. The rate of phosphor degradation increases with arc power and decreases with increased coating density. Lamp lumen depreciation (LLD) curves for different fluorescent lamps are shown in Figure 6-40.^{31,32} Protective coatings are sometimes used to reduce the phosphor degradation. Triphosphors are more stable and allow higher loading levels, as for example in T-5, T-8, compact, and sub-miniature lamps.

The deposit of electrode coating material evaporated dur-

ing lamp operation causes end darkening. This reduces UV radiation into the phosphors, thereby reducing light output near the ends.

Spectral Power Distribution and Chromaticity. Spectral power distribution data for several fluorescent lamps are shown in Figure 6-28. For a discussion of color and color rendering index, see Chapter 4, Color.

Temperature Effect on Operation. The luminous performance, light output, and color of a fluorescent lamp are dependent on the mercury vapor pressure within the lamp, which depends on temperature (Figure 6-41).

A fluorescent lamp contains a larger quantity of liquid mercury than will become vaporized at any one time. The excess liquid mercury condenses at the coolest point or points on the lamp. The mercury pressure within the lamp depends on the temperature of the coldest point or points. Lamp construction, design, and wattage, as well as luminaire design, ambient temperature, and wind or draft conditions, affect the cold point.

Lamps using mercury amalgams are available for extending the usable ambient temperatures to higher values. An amalgam is an alloy of mercury and other metals. The amalgam stabilizes and controls the mercury pressure. Placed in a fluorescent lamp, it determines the mercury vapor pressure in the discharge by absorbing or releasing mercury. Amalgams typically are used with compact fluorescent lamps where the bulb wall gets so hot that conventional temperature control techniques are less effective.

An amalgam keeps mercury pressure in the discharge close to its optimal value as the lamp temperature changes. As a result, an amalgam lamp can produce more than 90 percent of its maximum light output over a wide temperature

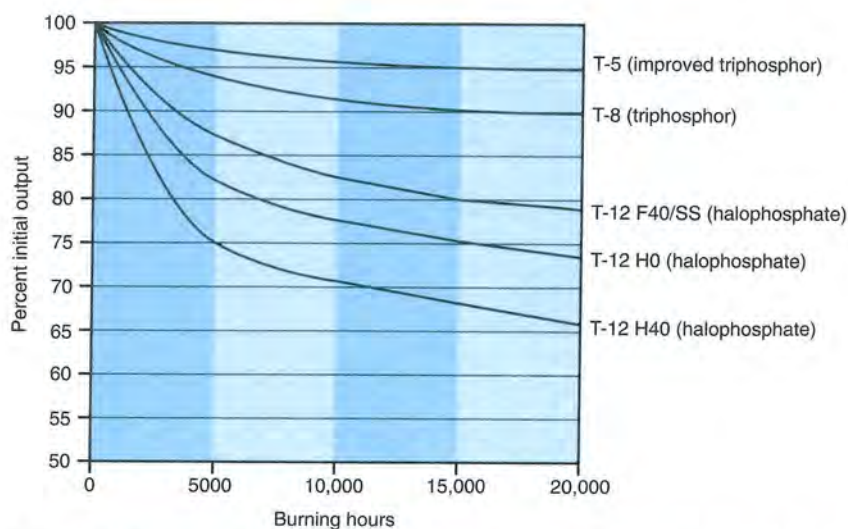


Figure 6-40. Fluorescent lamp lumen depreciation (based on operating on suitable ballast at 3 hr per start).

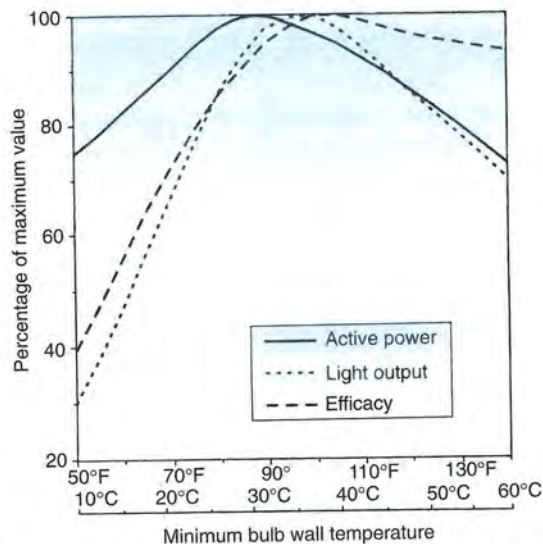


Figure 6-41. Typical fluorescent lamp temperature characteristics. Exact shape of curves will depend on lamp and ballast type; however, all fluorescent lamps have curves of the same general shape, since this depends on mercury vapor pressure.

range. Amalgam lamps also tend to maintain relatively constant light output at different operating positions compared to non-amalgam lamps. However, amalgam lamps can take longer to reach their full light output when turned on.³³

The internal temperature of a luminaire can adversely affect the life of some types of fluorescent lamps. High ambient temperatures not only lower the lamp's lumen output but also can change the lamp's electrical characteristics, bring these characteristics outside the design range of the ballast, and therefore allow more than rated current to flow. Long-term operation at higher currents shortens the life of the lamp.

As the temperature of the cold point changes, both the light output and the active power also change. Both active power and light output have optimum temperatures. Lamp efficacy, defined as light output divided by active power, is typically maximized at approximately 40°C (104°F) (Figure 6-41). Since temperatures within luminaires are typically above the optimum temperature for the lamps and since light loss beyond the optimum temperature is nearly linear, a rule of thumb can be used to estimate light loss as a function of high ambient temperatures. There will be a 1% loss in light output for every 1.1°C (2°F) increase in the ambient temperature above 38°C (100°F).³³

Compact fluorescent lamps often are more sensitive to the temperature of the operating environment than the standard straight tube lamps. In some cases the increased temperature inside the luminaire results in lower than rated light output. Additionally, the performance of many types of compact fluorescent lamps depends on their operating posi-

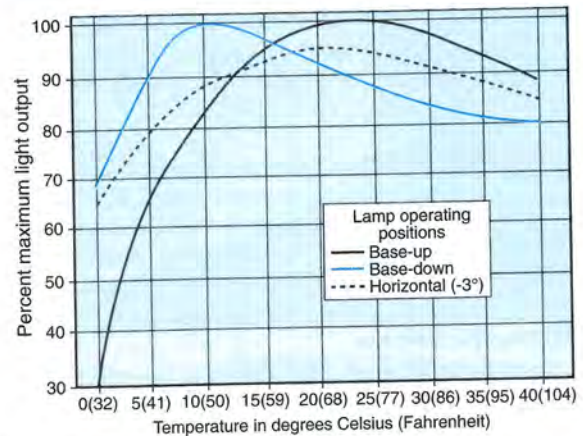


Figure 6-42. The light output characteristics for a nonamalgam compact fluorescent lamp show that the cool zone designed into the lamp geometry to help lower the minimum bulb wall temperature is most effective when the lamp operates base-up.

tion. Figure 6-42 shows the influence of operating position on typical compact lamps. Some compact fluorescent lamps employ amalgam technology that reduces the lamp sensitivity to burning position and lumen loss due to high and low temperature (Figure 6-43).

Most T-8 and T-12 lamps, which are intended primarily for indoor use, have been designed for their light output and luminous efficacy to reach optimum values at a minimum bulb wall temperature of 38°C (100°F). In well-designed luminaires, this temperature is typically reached when the

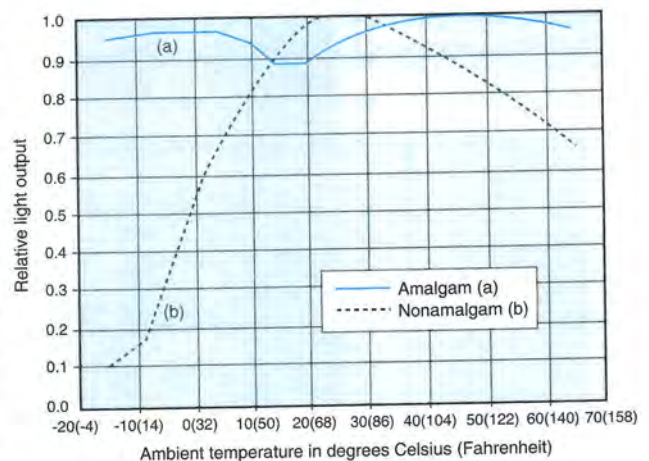


Figure 6-43. Comparison of relative light output vs. ambient temperature for two compact fluorescent lamp designs: one with amalgam (curve a) and one nonamalgam (curve b) in a base-up burning position.

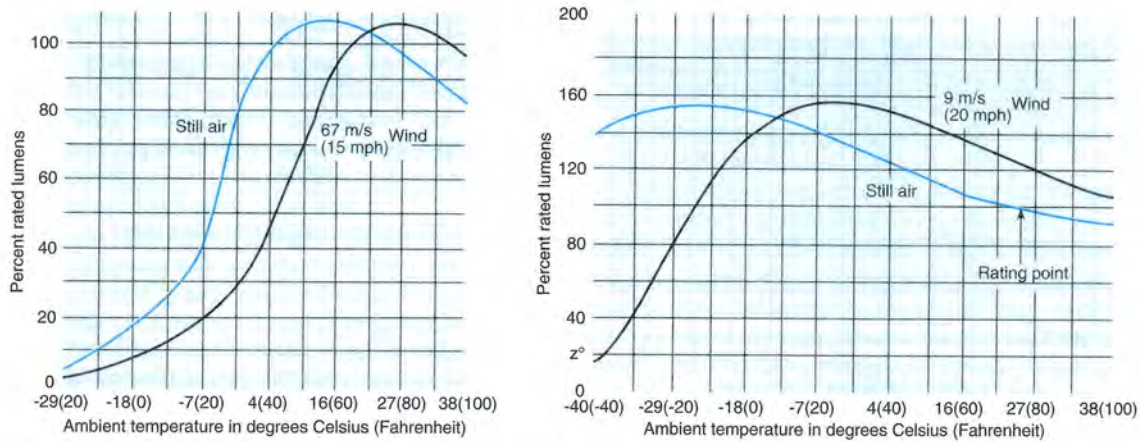


Figure 6-44. Light output versus ambient temperature. (Left) F96T12/HO fluorescent lamp. Light output falls to low values at temperatures below freezing. Loss in light at high ambient temperatures is much less. (Right) Two F72T12/HO lamps mounted in a typical floodlight. Performance of lamps designed for indoor application is considerably improved when operated in a suitable enclosure.

lamps are operated at rated power under usual indoor temperatures.

Curves for an 800-mA high-output fluorescent lamp are shown in Figure 6-44 (left). As these curves indicate, the light output falls to very low values at temperatures below freezing. Lamps intended for indoor operation display poor low-temperature performance unless protected by suitable enclosures. Figure 6-44 (right) shows the relationship between ambient temperature and light output for a typical outdoor floodlight using 800-mA high-output lamps. While considerable variation occurs with temperature change, satisfactory illumination is obtained for most winter temperatures.

Each lamp-luminaire combination has its own distinctive characteristic of light output as a function of ambient temperature. In general, the shape of the curve is quite similar for all luminaires, but the temperature at which the highest light output is reached can be different.

Effects of Temperature on Color. The color of light from a fluorescent lamp depends on the phosphor coating and also the mercury arc discharge. Each of these components reacts differently to temperature changes. Figure 6-45 shows a typical color shift characteristic of a halophosphate fluorescent lamp.

Color shift can be a concern when substantial differences in internal temperature exist between adjacent luminaires. This can arise from the proximity of certain luminaires to air diffusers or open windows; differences in ceiling cavity conditions or ceiling material with surface and recessed equipment; differences in the tightness of enclosures with enclosed equipment; differences in lamp loading or number of lamps in identical luminaires; and use of some of the luminaires as air diffusers in the air-conditioning system.

High-Frequency Operation of Fluorescent Lamps.

High-frequency electronic ballasts generally provide power to the fluorescent lamp in the range of 10 to 50 kHz from a 50- to 60-Hz power supply. The primary advantage of high-frequency electronic ballasts for fluorescent lighting systems is higher efficacy relative to the 60-Hz magnetic ballast systems.

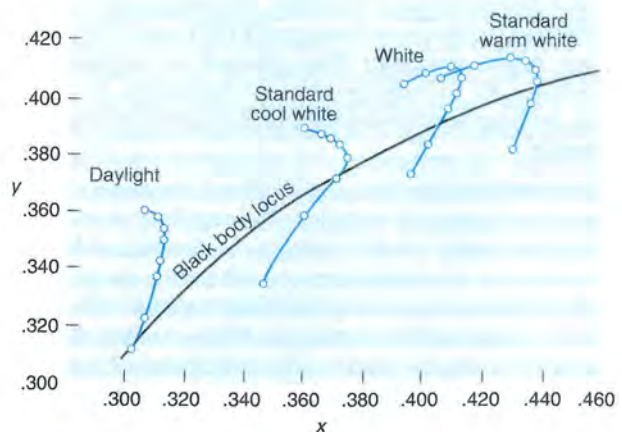


Figure 6-45. This CIE chromaticity diagram contains data for four different halophosphate fluorescent lamps. It shows that the color each lamp produces shifts toward the blue/green with increasing temperature. The lowest point on each curve is at -20°C (-4°F). Following each curve up and to the left as it bends over, the furthest point is at 120°C (248°F). Intermediate points are 20°C (36°F) apart. The chromaticity coordinates of any point are obtained from the x and y axis.

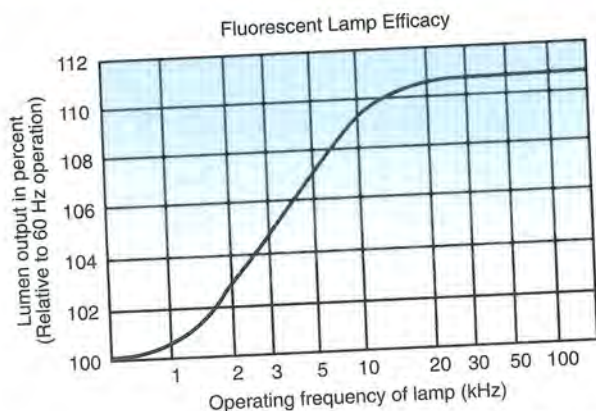


Figure 6-46. Lamp efficacy gain at constant lumen output vs. operating frequency for a 40-watt, T-12 rapid-start lamp.

As shown in Figure 6-46, efficacy increases rapidly with high-frequency operation until 20 kHz; in the range from 20 to 100 kHz, efficacy is constant. The improved performance of the fluorescent lamp at high frequencies has been attributed to two factors. First, a reduction in end losses is achieved by elimination of the oscillation on the anode half of the operating cycle. Second, an increase in efficiency of the lamp's positive column (major portion of the arc stream) is achieved by operating at lower wattage. In order to save energy, fluorescent lamps normally are operated at lower than rated wattage with high-frequency electronic ballasts while maintaining the lamp's rated lumen output.

In order to avoid audible noise, most electronic ballasts operate the lamp above 20 to 30 kHz. Another consideration in high-frequency operation of fluorescent lamps is radiated and conducted radio-frequency (RF) noise. The electronic ballast must have filter circuitry to constrain the conducted RF to within government regulations. In addition, the lamp current waveform must be chosen to limit RF intensity.

Radio Interference. The mercury arc in a fluorescent lamp emits electromagnetic radiation. This radiation can be received by nearby radios, causing an audible noise. Radio noise reaches the receiver either by radiation to the antenna or by conduction over the power lines. Because of the frequencies generated by the fluorescent lamp, radiated interference is ordinarily limited to the AM broadcast band and nearby amateur and communications bands. Radiated interference can be eliminated by moving the antenna farther from the lamp. A distance of 3 m (9.8 ft) is usually sufficient. Where this is not practical, shielding media, such as electrically conducting glass or certain louver materials, can suppress the noise below the interference level. FM, television, and higher frequencies rarely are affected by radiated interference but can be affected by conducted interference. Conducted interference can be suppressed by an electric fil-

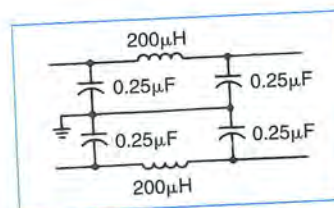


Figure 6-47. Typical radio interference filter.

ter in the line at the luminaire. Figure 6-47 shows a typical design. Luminaires with this type of filtering and appropriate shielding material have been qualified under pertinent military specifications for sensitive areas. Most instant-start ballasts and starters for preheat circuits have capacitors for reducing radio interference.

Infrared Interference with Compact Fluorescent Lamps.

The use of infrared (IR) radiation for transmitting data and control signals has increased in popularity for equipment such as television and video cassette recorders, computers, and medical devices. Such equipment generally uses IR receivers that, in North America, operate at carrier frequencies from 33 kHz to 40 kHz, and some at 56 kHz. With the increased use of compact fluorescent lamps operated on electronic ballasts, more interference problems have been reported. If the operating frequency of the compact fluorescent ballast or its second harmonic, which is the power supply frequency, is within the frequency band of the appliance IR receiver, interference can occur. To reduce or eliminate this interference, one should move the lamp to a new position or use other lamp and ballast combinations where frequency matching does not occur. Current electronic ballast designs take into account this potential interference by using operating frequencies that minimize this interaction. Additionally, IR receivers now contain improved coding that is less sensitive to stray IR radiation.

Flicker and Stroboscopic Effect. The light output of a fluorescent lamp varies with instantaneous power input. Operating on a magnetic ballast with a 60-Hz power input frequency, the resulting 120-Hz variation coupled with phosphor persistence makes the fluctuating light output too rapid for most people to perceive. This assumes, however, that the power input is free of electrical noise. The presence of electrical noise from other equipment can result in frequencies that manifest themselves as visible flicker. Under noise-free operating conditions, the flicker index for typical fluorescent lamps operated with electromagnetic ballasts ranges from 0.01 to approximately 0.1, and is much lower when operated with high frequency electronic ballasts. For a discussion about flicker and the stroboscopic effect, including the definition of the flicker index, see Chapter 2, Measurement of Light and Other Radiant Energy.

Lamp Operation and Auxiliary Equipment

General. Like most arc discharge lamps, fluorescent lamps have a negative volt-ampere characteristic and therefore require an auxiliary device to limit current flow. This device, called a ballast, might also provide a voltage sufficient to start the arc discharge. This voltage can vary between 1.5 to 4 times the normal lamp operating voltage.

The life and light output ratings of fluorescent lamps are based on their use with ballasts providing proper operating characteristics, which have been established in the ANSI standards for dimensional and electrical characteristics of fluorescent lamps (C78 Series). Ballasts that do not provide proper electrical values might reduce either lamp life or light output or both. This auxiliary equipment requires electrical power and therefore reduces the system efficacy below that based on the power requirements of the lamp.

Lamp Starting. The starting of a fluorescent lamp occurs in two stages. First, the electrodes must be heated to their emission temperatures. Second, a sufficient voltage must exist across the lamp to ionize the gas in the lamp and develop the arc. In some starting systems, a voltage is applied between one of the electrodes and ground to help ionization.

As the ambient temperature is reduced, it becomes more difficult to start fluorescent lamps. Higher voltages are required to reliably start lamps at low temperatures. For efficient lamp and ballast operation, specific ballasts are generally available for each of the following temperature ranges: above 10°C (50°F) for indoor applications, above -18°C (0°F) for outdoor temperature applications, and above -29°C (-20°F) for outdoor temperature applications.

Three different means of starting lamps with magnetic ballasts have been developed. Preheat starting requires an automatic or manual starting switch. Instant starting requires a high ballast open circuit voltage. Rapid starting, the most commonly used starting circuit, continuously heats the electrodes, obviating high voltages and starting switches. Several magnetic circuits are shown in Figure 6-48. In general, for operation on magnetic ballasts, there are differences between lamp designs for different starting methods; therefore, it is important to match the lamp to the starting circuit. The lamp description normally identifies the proper circuit, that is, preheat, rapid, or instant start.

For electronic ballasts, new techniques for starting fluorescent lamps have been developed. Electronic ballasts have been introduced that can instant start most rapid-start fluorescent lamps. Additionally, hybrid electronic starting methods are available that combine characteristics of rapid and preheat starting. Electronic ballasts are also available with a soft starting sequence, which is designed to minimize damage to the electrodes during starting and therefore to lengthen lamp life.

Preheat Lamp and Ballast Operation. In preheat circuits, the lamp electrodes are heated before application of the high voltage across the lamp. Lamps designed for such operation have bipin bases to facilitate electrode heating. Many preheat-starting compact fluorescent lamps have the starting devices built into the lamp base.

The preheating requires a few seconds, and the necessary delay usually is accomplished by an automatic switch that places the lamp electrodes in series across the output of the ballast. Current flows through both electrode filaments, heating them. Subsequently, the switch opens, applying the voltage across the lamp. Due to the opening of the switch under load, a transient voltage (an inductive spike) is developed in the circuit, which aids in ignition of the lamp. If the lamp does not ignite, the switch closes and reheats the filaments. In some systems, preheating is accomplished by a manual switch.

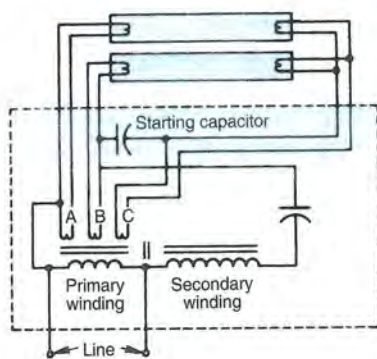
The automatic switch is commonly called a starter. It can incorporate a small capacitor (0.006 μ F) across the switch contacts to shunt high-frequency oscillations that might cause radio interference.

Ballasts are available to operate some preheat lamps without the use of starters. These ballasts use the rapid-start principle of lamp starting and operating and popularly are called trigger start ballasts.

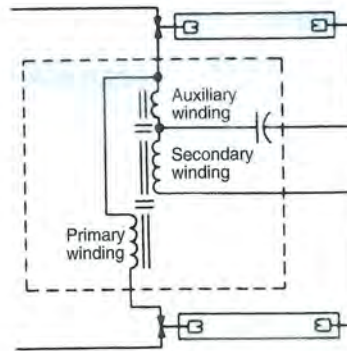
Starters For Preheat Circuits. The operation of a preheat circuit requires heating of the electrodes prior to application of voltage across the lamp. Preheating can be effected by use of a manual switch or a switch that is activated by application of voltage to the ballast circuit. A number of automatic switch designs are commercially available. Diagrams for two designs are presented in Figure 6-49.

Thermal Switch Starter. A diagram of a thermal switch starter is presented in Figure 6-49a. Initially the silver-carbon contact of the thermal starter is closed, placing the electrodes in series with the parallel combination of the bimetal and the carbon resistor. Upon closing the ballast supply circuit, the output voltage of the ballast is applied to this series-parallel wiring combination. The current heats the bimetallic strip in the starter, causing it to open the silver-carbon contact. The time of opening is sufficient to raise the temperature of the electrodes to approximately its normal operating value. Upon opening the circuit, the ballast output voltage in series with an inductive spike (kick) voltage is applied to the lamp. If the lamp ignites, its normal operating voltage maintains a low current through the carbon resistor, developing and transferring sufficient heat to the bimetal to hold its contact open thereafter.

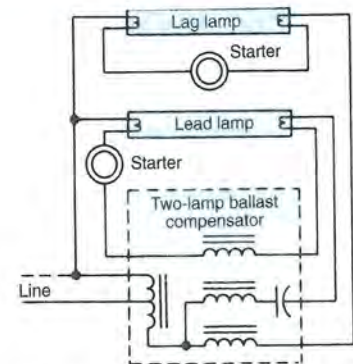
Should the lamp fail to start on the first attempt, the ballast open-circuit voltage applied to the carbon resistor heats the bimetal sufficiently to cause the silver contact to move against the third contact. This short-circuits the carbon resistor, permitting preheating current to flow through the electrodes. As the bimetal cools, the circuit through the third contact is opened, resulting in the application of the circuit



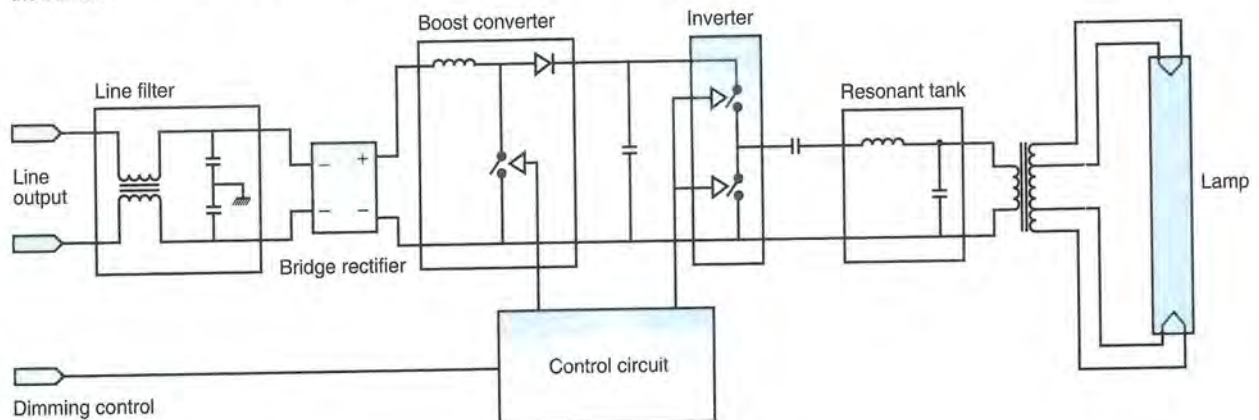
(a) Two-lamp rapid-start high power factor. Used for rapid-start, high output, and extra high output lamps, for both indoor and low temperature applications. The small capacitor shunted across one lamp momentarily applies nearly all of the ballast secondary voltage across the other lamp. The lamp cathodes are continuously heated by the cathode heating windings (A, B, and C) in the ballast.



(b) Two-lamp series-sequence instant-start high power factor. Used in instant (slimline) indoor units. Lamps start in sequence with auxiliary winding helping to start first lamp. Note disconnect lamp-holder connection that removes power from the ballast primarily when lamps are being changed, thus preventing electric shock.



(c) Two-lamp lead-lag preheat, high power factor. Used in 40-watt and 90-watt preheat-type general luminaires. Note compensator winding, which is needed to produce sufficient preheat current in the lead circuit.



(d) Hot cathode rapid-start lamps with electronic ballasts

Figure 6-48. Typical fluorescent lamp circuits.

voltage to the lamp again. This making and breaking of the circuit through the third contact continues until the lamp ignites. The bimetal circuit is held open thereafter as noted above. The carbon contact circuit functions only when the line voltage is initially applied to the ballast.

Thermal-switch starters require some power (0.5 to 1.5 W) during lamp operation, but their design ensures positive starting by providing an adequate preheating period, a high induced starting voltage, and characteristics inherently less susceptible to line voltage variations. For these reasons they give good all-around performance under adverse conditions, such as direct-current operation, low ambient temperature, and varying voltage.

Glow-Switch Starter. The circuit for this starter is presented in Figure 6-49b. The bulb is filled with an inert gas chosen for the voltage characteristics desired. On starting, the line switch is closed. There is almost no voltage drop in the ballast, and the voltage at the starter is sufficient to produce a glow discharge between the contacts. The heat from the glow distorts the bimetallic strip, the contacts close, and electrode preheating begins. This short-circuits the glow discharge so that the bimetal cools, and in a short time the contacts open. The open-circuit voltage in series with an inductive spike voltage is applied to the lamp. If the lamp fails to ignite, the ballast open-circuit voltage again develops a glow in the bulb, and the sequence is repeated until the lamp ig-

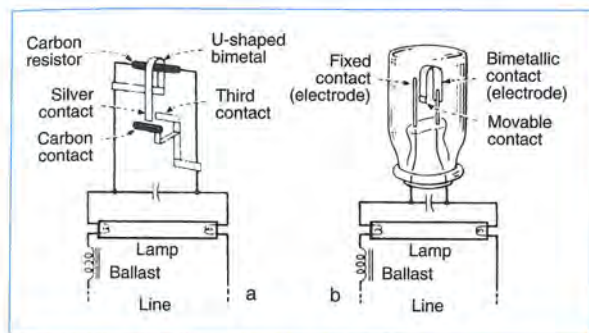


Figure 6-49. Starter switches for preheat cathode circuits: (a) thermal type; (b) glow switch type.

nites. During normal operation, there is not enough voltage across the lamp to produce further starter glow, so the contacts remain open and the starter requires no power.

Cutout Starter. This starter resets either manually or automatically. It is designed to prevent repeated blinking or attempts to start a deactivated lamp. This type of starter should be good for at least ten or more renewals.

Lamp Failure in Preheat Circuit. Starters that provide no means for deactivation when a lamp fails will continue to attempt to start the lamp. The lamp might repeatedly blink on and off, and the ballast or starter will eventually fail. Thus it is important to remove a failed preheat lamp immediately.

Instant-Start Lamp and Ballast Operation. Arc initiation in instant-start lamps depends solely on the application of a high voltage across the lamp. This voltage (400 to 1000 V) ejects electrons from the electrodes by field emission. These electrons flow through the tube, ionizing the gas and initiating an arc discharge. Thereafter, the arc current provides electrode heating. Instant-start lamps need only a single contact at each end. A single pin is used on most instant-start lamps. These are commonly called slim-line lamps. A few instant-start lamps use bipin bases with the pins connected internally. In the case of lamps designed for instant starting at 400 to 1000 V open circuit, it is necessary to provide some means of counteracting the effect of humidity on the capacitive lamp-ground current that initiates the necessary glow discharge. Most manufacturers coat the outside of bulbs of this type of lamp with a transparent, nonwetting material; others apply a narrow conducting strip along the bulb. A grounded conducting plate, such as a metal reflector near the lamp, commonly known as a starting aid, is necessary to obtain the lowest lamp starting voltage.³⁴

Rapid-Start Lamp and Ballast Operation.³⁵⁻³⁸ Lamps designed for rapid-start operation typically have low-resistance cathodes. Normally, the cathodes are heated continuously by the application of cathode voltage while the lamps are in operation. In some energy-saving circuits, the cathode voltage is reduced or disconnected after the starting of the lamps. Heating is accomplished through low-voltage wind-

ings built into the ballast or through separate low-voltage transformers designed for this purpose. This results in a starting-voltage requirement similar to that of preheat lamps. Lamps usually start in approximately one second, which is the time required to heat the filaments to their proper temperature.

A starting aid, consisting of a grounded conducting plate, is required for reliable starting. For lamps operating at 500 mA or less, the nominal distance between the lamp and a 25 mm (1-in.) wide conducting plate is 13 mm (0.5 in.); for lamps operating at currents greater than 500 mA, the nominal distance to the conducting strip is 25 mm (1 in.).

Rapid-start lamps are coated with a transparent nonwetting material to counteract the adverse effect of humidity in lamp starting. All 800-mA and most 1500-mA lamps operate on the rapid-start principle. Forty-watt and circline lamps designed for rapid-start service also can be used in comparable preheat circuits.

Electronic Ballast Starting. All three starting methods are employed in electronic ballasts. When applied to electronic ballasts, the differences between the rapid-start and the preheat technique become less significant. The preheat designs use internal timing components that delay the full open-circuit voltage while applying power to the electrodes for preheating. After starting, the power to the electrodes is reduced to almost zero. Most of the rapid-starting systems do not rely on a potential to ground to aid the start as with the magnetic ballast. The starting method is similar to the preheat technique except that the electrode voltage usually remains after the lamp starts. Electronic ballasts have been designed to "instant-start" rapid-start fluorescent lamps. Typically there may be a reduction in expected life when operated in this manner.

Ballasts

Magnetic Ballasts. The construction of a typical thermally protected rapid-start magnetic ballast is shown in Figure 6-50. The components include a transformer-type core and coil. A capacitor might be included. These components are the heart of the ballast, providing sufficient voltage for lamp ignition and lamp current regulation through their reactance.

The core-and-coil assembly is made of laminated transformer steel wound with copper or aluminum magnet wire. The assembly is impregnated with a nonelectrical insulation to aid in heat dissipation and, with leads attached, is placed in a case. The case is filled with a potting material (e.g., hot asphalt) containing a filler such as silica. This compound completely fills the case, encapsulating the core and coil and the capacitor. The base is then attached.

The average ballast life at a 50% duty cycle and a proper ballast operating temperature is normally estimated at twelve years. Ballast life is reduced by higher temperatures or longer duty cycles.

Most fluorescent lamp ballasts used indoors should have an internal thermal protection device. This prevents misap-

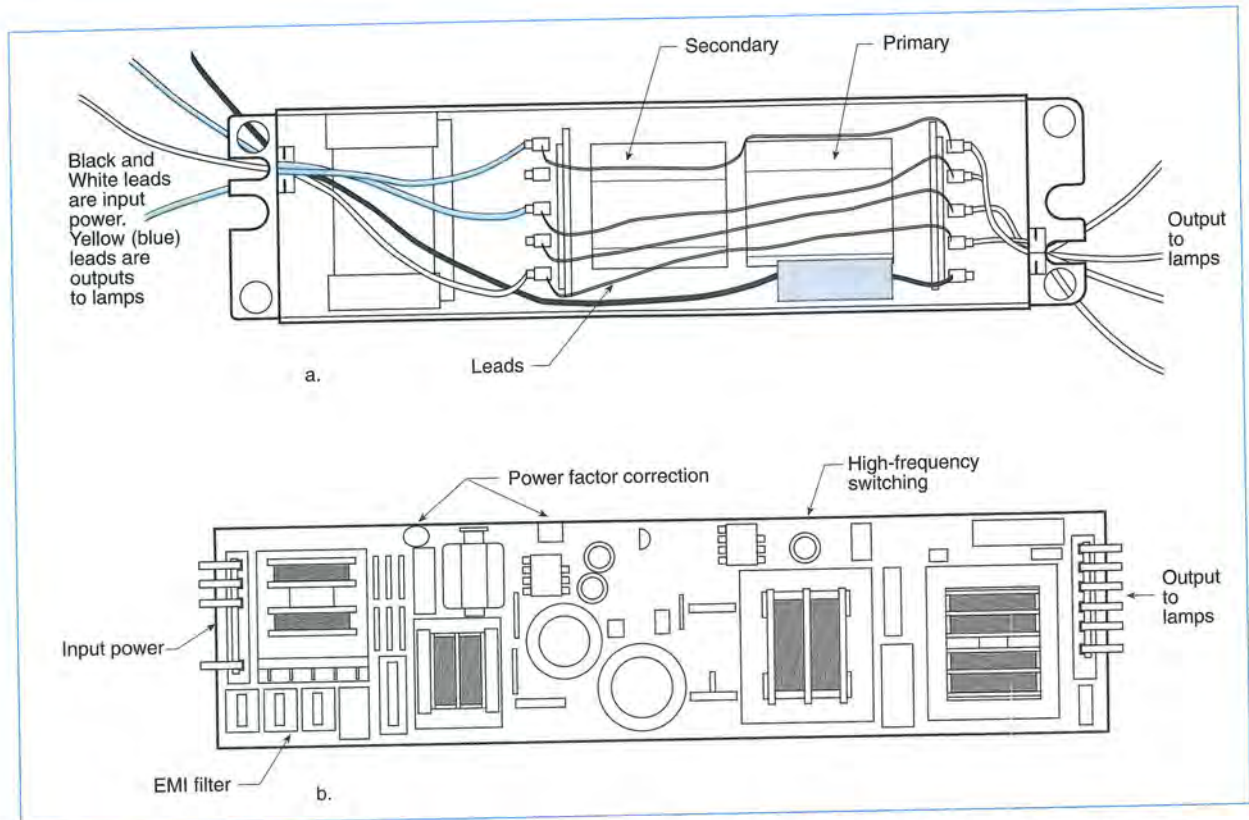


Figure 6-50. Components of a magnetic ballast (a) and high-frequency electronic ballast (b) for a linear fluorescent lamp.

plication of the ballast in high-temperature applications and protects against failure and undesirable conditions that can occur at end of ballast life. In the United States the thermally protected ballast approved by Underwriters Laboratories is known and marked or labeled as "Class P."

Because of the magnetic components in most ballasts, including some electronic ballasts, vibrations can cause audible noise. The noise depends on several factors, including the construction, mounting, number, and spacing of the ballasts and luminaires, and the acoustical characteristics and use of the room.

Ballast manufacturers publish sound ratings that indicate the relative sound-producing potential of their different models. These ratings are based on the experience of the model in different ambient conditions, operating in places ranging from a quiet school room, church, or office to a relatively noisy business office, store, or factory. An A rating means the ballast/luminaire hum probably will not be noticeable in quiet spaces. A B rating is borderline in the quiet applications, but will not be a problem in the noisier places. The C rating should be used only in noisy places like factories.

Electronic Ballasts.³⁹ The operating frequency of electronic ballasts is chosen to be high enough to increase the lamp efficacy and to make ballast noise inaudible, but not so high as to cause electromagnetic interference (EMI). Electronic ballasts also provide a level of light output regulation that is unavailable in totally passive, magnetic ballasts. Designs are available for the rapid- and instant-start of lamps. Some electronic ballasts are designed to operate up to four lamps each. Many are made in the same size and shape as magnetic units in order to ease direct replacement. Some designs have circuits that keep the line-current harmonic distortion below 20% and provide a power factor in excess of 90%. Some ballasts also employ circuits to limit the current in-rush when power is applied to the ballast. This in-rush, which is a result of the electrolytic capacitors of an electronic ballast charging up, occasionally had been reported as a problem for switches and relays used to turn power to the ballasts on and off. Electronic ballasts also can be designed to operate with dc and low-voltage systems for applications in buses, airplanes, trailers, and battery-operated emergency systems.

In addition, it has been reported that some T-5 and

smaller fluorescent lamps have problems at the end of life in field applications. When a fluorescent lamp fails, typically one of the electrodes becomes an open circuit. This can create an asymmetric lamp current operating condition that can produce high local heating, which in turn can crack the lamp bulb or overheat and deform the lamp base. ANSI specifications for magnetic ballasts⁴⁰ have been revised to address the end-of-life operation of these lamps.

Reduced-Wattage Ballasts. Ballasts are available that operate standard lamps at 50 to 80% of their rated wattage. Energy-saving lamps should not be used in combination with these ballasts, since the arc will tend to waver.

Energy-Saving Ballasts. Energy-saving ballasts have lower power losses than the more common magnetic ballasts. These may be rated by Certified Ballast Manufacturers (CBM) and are used either with common lamps or with reduced-wattage lamps. For example, power losses in two-lamp 40-W rapid-start ballasts have been reduced by 4 to 5 W per lamp over common magnetic ballasts. A typical two-lamp 40-W unit with a low-loss energy-saving ballast dissipates approximately 86 W, compared to approximately 95 W for most magnetic ballasts.

Energy-Saving Systems. Specialized lamp-and-ballast combinations are available to achieve energy savings. These include a 32-W T-8 (4-ft) lamp with a high-efficiency ballast and a 28-W T-12 lamp, also with a high-efficiency ballast, having internal solid-state switches that turn off the usual rapid-start cathode heater voltage. These ballasts can also operate a 34-W reduced-wattage lamp. Power reducers are also available for saving energy. These solid-state electronic devices are wired in series with the lamp ballast to reduce operating wattage. Note that a reduction in light output results.⁴¹

Ballast Power Factor. The power factor is defined as the ratio of input wattage to the product of root mean square (rms) voltage and rms current. It represents the amount of current and voltage that the customer is actually using as a fraction of what the utility must supply. High power factor is defined as being above 90%. A ballast with low power factor draws more current from the power supply and therefore, larger supply conductors might be necessary. Low-power-factor ballasts are more common with compact fluorescent systems than for 4-ft and 8-ft fluorescent systems. Some public utilities have established penalty clauses in their rate schedule for installations with low power factor. Some utilities require high power factor equipment.

Ballast Factor and Ballast Efficacy Factor. The ballast factor is defined by ANSI (ANSI C82.2-1984)⁴⁰ as the relative light output of a lamp operated on the ballast with respect to the same lamp on a reference ballast, usually expressed in percent. The reference ballasts are discussed in detail for each fluorescent lamp type in the applicable ANSI lamp standards. The ballast efficacy factor (BEF) is defined as the ballast factor in percent, divided by the total input power in watts. In the United States, federal regulation sets

limits on the BEF of some ballasts for 1.22 m (4-ft) and 2.44 m (8-ft.) fluorescent lamps, summarized in the following table:

U.S. and Canadian Standards for Ballast Efficacy Factor

Lamp Type	Ballast Input Voltage (V)	Total Nominal Lamp Active Power (W)	BEF (minimum)	
			U.S. Standard	Canadian Standard
One F40T12	120	40	1.805	1.805
	277	40	1.805	1.805
	347	40	N/A	1.750
Two F40T12	120	80	1.060	1.060
	277	80	1.050	1.050
	347	80	N/A	1.020
Two F96T12	120	150	0.570	0.570
	277	150	0.570	0.570
	347	150	N/A	0.560
Two F96T12/HO	120	220	0.390	0.390
	277	220	0.390	0.390
	347	220	N/A	0.380
Two F32T8	120	64	N/A	1.250
	277	64	N/A	1.230
	347	64	N/A	1.200

In addition to the federal regulation, some states might impose additional restrictions on the above or on additional lamp types. Specifically excluded are dimming ballasts, ballasts intended for use in ambient temperatures of -17.8°C (0°F) or lower and ballasts with power factor less than 90% that are designed for residential use (in buildings up to three stories). Moreover, some utility companies have specified a minimum BEF and ballast factor in their rebate programs for energy-efficient equipment. They generally pertain to the same lamps as the U.S. federal regulation.

Harmonics. Line-current harmonics are those components of the line current that oscillate at low integer multiples of the fundamental frequency of the power supply. For instance, in North America, the fundamental frequency is 60 Hz, the second harmonic is 120 Hz, the third harmonic is 180 Hz, and so forth. Switching in modern solid-state electronic ballasts can cause substantial line-current harmonics when corrections are not implemented in the ballast. This can be especially harmful in three-phase installations if the third-harmonic current is large. The third harmonic and its multiples add in the neutral wire, while the fundamental currents tend to cancel one another there. If the third harmonic is 33.3% of the fundamental, then the total third harmonic in the neutral wire is equal to the fundamental in the phase wires. This can cause problems, including overheating, if the neutral wire is not properly sized.

For these reasons, ANSI C82.11⁴² places limits on the harmonic content in the line current for electronic ballasts employed in commercial and residential lighting applications. In the United States, several utility companies have in-

Figure 6-51. General Characteristics of Commonly Used Ballasts

	Input Power (watts)	Ballast Factor	Efficacy (lumens/watt)	Power Factor	Current THD
Ballast for 2-F32T8 fluorescent lamps					
Energy-efficient magnetic	70	0.94	78	≥ 0.9	≤ 20%
Hybrid	61	0.86	82	≥ 0.9	≤ 20%
Electronic	62	0.88	82	≥ 0.9	≤ 20%
Electronic, reduced light output	51	0.71	81	≥ 0.9	≤ 20%
Instant-start electronic*	63	0.95	87	≥ 0.9	≤ 20%
Ballast for 2-F34T12 fluorescent lamps					
Energy-efficient magnetic	72	0.87	68	≥ 0.9	≤ 20%
Hybrid	66	0.88	75	≥ 0.9	≤ 20%
Hybrid, reduced light output	58	0.81	78	≥ 0.9	≤ 20%
Electronic	62	0.88	79	≥ 0.9	≤ 20%
Electronic, reduced light output	52	0.73	79	≥ 0.9	≤ 20%

* Instant-start ballasts can cause 25% reduction in lamp life compared to rapid-start ballasts when operated at 3-hour-per-start cycling testing.

cluded harmonics as an issue in their rebate programs intended for customers who purchase energy-efficient equipment. Early electronic ballasts typically had high total harmonic distortion (THD) content, which led to the development of these standards. Figures 6-51 and 6-52 list THD and electrical characteristics of fluorescent lamps, respectively.

Fluorescent Lampholders. Lampholders are designed for each lamp base style. Typically several versions of each are available to allow various spacings and mounting methods in luminaires (Figure 6-53). Proper spacing should be maintained between lampholders in luminaires to ensure satisfactory electrical contact. Manufacturers' catalogs should be consulted for dimension and spacing information on any particular lampholder type.

When fluorescent lamps are used in circuits providing an open-circuit voltage in excess of 300 V, or in circuits that permit a lamp to ionize and conduct current with only one end inserted in the lampholder, electrical codes usually require some automatic means for opening the circuit when the lamp is removed. This usually is accomplished by the lampholder so that on lamp removal, the ballast primary circuit is opened. The recessed contact bases on 800- and 1500-mA fluorescent lamps eliminates the need for this disconnect feature in lampholders for these lamps.

Lamp bases for many compact fluorescent lamps are constructed with unique pin-and-keyway systems to prevent installing the wrong lamp. Universal lampholders that allow lamps of any wattage to fit should be avoided.

Figure 6-52. Fluorescent Lamp Electrical Characteristics

Lamp Description	Bulb Diameter (in.)	Bulb Watts	Base (End Caps)	Normal Length		Min. Required RMS Voltage Across Lamp for Reliable Starting (V)	Operating Current (mA)	Operating Voltage (V)	Cathode Heaters (Low Resistance)	
				(mm)	(in.)				Volts	Maximum Watts
F32T8	1	32	Med. Bipin	1200	47.25	200	265	137	3.6	1.7
FT36W/2G11RS	5/8	38.1	2G11	419	16.49	230 single lamp	430	110	3.6	continuous
CFL26	1/2	26	G24d-3	169	6.65	198	325	105	preheat >10 sec	420mA
T5	5/8	28	Min. Bipin	1200	47.25	375	210	107	preheat <2 sec	210mA
T5/HO	5/8	54	2G11	830	32.6	425	400	135	preheat <2 sec	700mA
40T12/SS	1	34-35	Med. Bipin	1200	47.25	1 = 200; 2 = 256	460	79	3.6	—
96T12/SS (Slimline)	1	60	Single pin	2400	94.48	565	440	157	none	continuous
96T12/HO/SS (Rapid start)	1	97	Recess D. C.	2400	94.48	296 2 lamps	830	126	3.6	continuous
			G5 Min. Bipin	1149	45.25					
			G5 Min. Bipin	1149	45.25					



Figure 6-53. Typical lampholder designs.

Dimming of Fluorescent Lamps.⁴³⁻⁴⁵ Many types of fluorescent lamps are suitable for dimming. Dimming fluorescent lamps differs from dimming incandescent lamps in two key ways. First, fluorescent dimmers do not provide dimming to zero light as do incandescent dimmers. However, products are available to dim to as low as 0.5 to 25% of maximum light output. Second, when dimming fluorescent lamps, the correlated color temperature varies substantially less over the dimming range than incandescent lamps.

Dimming is achieved by reducing the effective lamp current. When doing so, it is necessary to supply the full starting voltage and to maintain the restriking voltage necessary at each 60-Hz half cycle. This is especially true when operating the lamp at low light output. It is also necessary to provide filament heating for all except cold cathode lamps in order to maintain the required electron emissions from the electrodes at all intensities.

Early magnetic dimming ballasts achieved dimming by lowering the primary voltage to the ballast transformer. Such a dimming system can be used with two-pin cold cathode fluorescent lamps in a series circuit as shown in Figure 6-54. With this arrangement, it is possible to reduce the luminous intensity to approximately 10% of maximum light output. The performance of magnetic dimming ballasts can be improved by adding one or more of the following features: filament transformers to provide filament heat, pulse networks to provide the required restriking voltage at low intensities, and high-frequency keep-alive current to maintain the discharge when the line current is interrupted during part of the 60-Hz cycle. These components can be packaged

together with the magnetic ballast or be separately installed in the luminaires as dimming adapters.

Controls for the magnetic dimming ballasts are available in two-wire and three-wire configurations. The two-wire systems have a limited dimming range, typically 25% light output at the low end, but can be retrofitted with existing wiring in most cases. The three-wire configurations bring a control wire to an external control, such as a wall station. This flexibility allows for a substantial improvement in the dimming performance.

For electronic dimming ballasts, there are several control schemes available. Some manufacturers use a three-wire scheme as described above, so that electronic dimming ballasts can directly replace magnetic dimming ballasts without affecting the control unit. Other three-wire implementations also require the control to be changed. Yet other manufacturers use four-wire systems where two of the wires are used

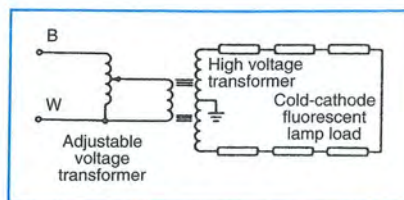


Figure 6-54. Typical dimming circuit for series-connected cold-cathode lamps.

for the dimming signal and the other two to carry the main lamp current.

Most currently available fluorescent lamp dimming systems incorporate electronic ballasts that use high-frequency (typically 20 to 50 kHz) switching of the lamp current. They are designed to be used with four-pin, rapid-start, and compact fluorescent lamps and are available for several lamp diameters and lengths. Electronic dimming ballasts generally are more efficient and less bulky than their autotransformer predecessors. Furthermore, lamp flicker can be substantially reduced with electronic dimming ballasts.

Most electronic ballasts offer energy savings approximately proportional to the reduction in light output (Figure 6-55). This is particularly true at dimmer settings above 25 to 50% luminous output. Furthermore, four-pin construction allows cathode heating when dimming. This is important since it extends lamp life and eliminates flicker when properly implemented. It is also advisable to select premium-quality knife-edge sockets rather than leaf-spring contacts. This ensures that cathode heating is reliably supplied. Finally, solid-state dimmers are substantially quieter (less humming) than their magnetic predecessors.

The performance of a fluorescent dimming system might not be satisfactory if the lamp is not correctly matched with the dimming ballast and the controller. In particular, reduced wattage, energy-saving retrofit lamps should not be used in dimming systems, unless so recommended by the dimmer manufacturer. Doing so might shorten the life of the lamp and ballast.

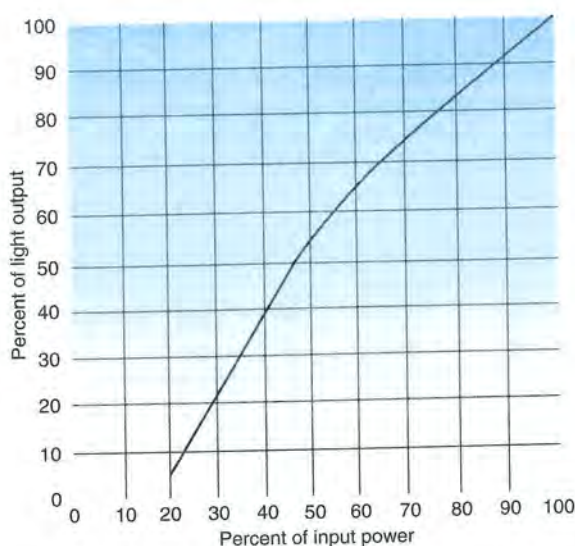


Figure 6-55. Light output vs. input power for a typical 40-watt 120-volt rapid-start fluorescent dimming system.

Flashing of Fluorescent Lamps.^{46,47} Cold cathode and rapid-start or preheat-start hot cathode fluorescent lamps can be flashed and still maintain good performance. Cold cathode lamps are flashed through control of either the transformer primary or secondary voltage. Hot cathode lamps can be flashed by means of a special ballast that turns the arc current on and off but keeps the cathode heating on. An external flashing device is required with either system. This unit must be rated for the voltage and current involved, and it is recommended that separate contacts be used for each ballast to prevent circulating currents between ballasts. Flashing of fluorescent lamps is sometimes used in advertising.

HIGH-INTENSITY DISCHARGE LAMPS

High-intensity discharge (HID) lamps include the groups of lamps commonly known as mercury, metal halide, and high-pressure sodium. The light-producing element of these lamp types is a wall-stabilized arc discharge contained within a refractory envelope (arc tube) with wall loading in excess of 3 W/cm² (19.4 W/in.²).

Lamp Construction and Operation

All high-intensity discharge lamps produce light by means of an electrical arc discharge contained in an arc tube inside the bulb. The arc tube contains tungsten electrodes that terminate the arc discharge at each end of the arc tube. The arc tube also contains a starting gas that is relatively easy to ionize at low pressure at normal ambient temperatures. This starting gas is usually argon or xenon or a mixture of argon, neon, or xenon, depending on the type of HID lamp. The arc tube also contains metals or halide compounds of metals that, when evaporated into the arc discharge, produce characteristic lines of radiant energy. Each type of HID lamp produces light related to the type of metal that is contained in the arc. Mercury vapor lamps produce light by exciting mercury atoms; high-pressure sodium lamps produce light by exciting sodium atoms; and metal halide lamps produce light by exciting several different atoms and molecules, primarily sodium, scandium, thulium, holmium, and dysprosium.

The arc tube is contained inside a soft or hard glass outer bulb to protect the arc tube and internal electrical connections from the environment. The outer bulb absorbs the majority of UV energy radiated by the arc tube while allowing light to pass through. The outer glass bulb can be coated with a diffusing material to reduce the source brightness of the lamp. In mercury vapor and metal halide lamps, this diffusing coating can be a color-correcting phosphor that uses UV energy radiated by the arc tube to improve the lamp's overall color rendering properties.

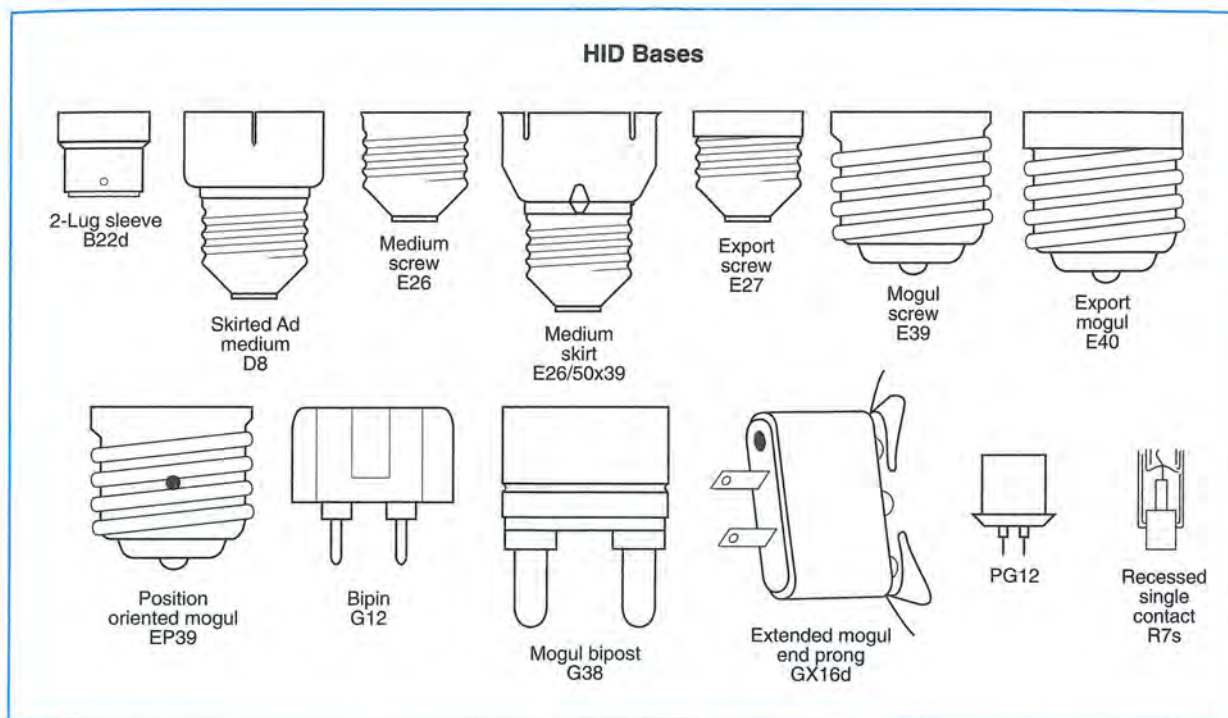


Figure 6-56. Common HID lamp bases (not to scale). ANSI designations are shown.

Within the outer bulb there are wires suitable for high temperatures to conduct electricity to the arc tube and structural components to support the arc tube. There might be other components, including resistors or diodes used to help start the arc discharge, and devices called getters to purify the atmosphere in the outer lamp. The atmosphere in the outer bulb might be a low-pressure gas (usually nitrogen) or, in many cases, a vacuum.

HID lamps have screw bases (medium or mogul) made from brass, nickel, or special alloys to minimize corrosion. Some HID lamps have special bipin bases or pairs of single contact bases at each end of the lamp to provide electrical connections (Figure 6-56).

If the outer bulb is broken and the arc tube continues to operate, the lamp emits a significant amount of UV energy. Exposure to people beyond about 15 minutes can produce severe erythral effects (skin reddening) or eye damage (see Chapter 5, Nonvisual Effects of Optical Radiation, for more details). Self-extinguishing lamps usually contain a tungsten filament in place of a portion of nickel wire that will oxidize quickly and separate, extinguishing the electrical arc and turning the lamp off. The lamp is then inoperative and needs to be replaced.

Mercury Lamps.⁴⁸⁻⁵² In mercury lamps, light is produced by the passage of an electric current through mercury vapor. Since mercury has a low vapor pressure at room tempera-

ture, and even lower when it is cold, a small amount of more readily ionized argon gas is introduced to facilitate starting. The original arc is struck through the ionization of this argon. Once the arc strikes, its heat begins to vaporize the mercury, and this process continues until all of the mercury is evaporated. The amount of mercury in the lamp essentially determines the final operating pressure, which is 200 to 400 kPa (29 to 58 lb/in.²) in the majority of lamps.

The electrodes of mercury lamps usually are made of tungsten, in which the emission material, composed of several metallic oxides, is embedded within the turns of a tungsten coil protected by an outer tungsten coil. The electrodes are heated to the proper electron-emissive temperature by bombardment energy received from the arc.

Most mercury lamps are constructed with two envelopes: an inner envelope (arc tube) that contains the arc, and an outer envelope that (1) shields the arc tube from outside drafts and changes in temperature; (2) usually contains a stable, low-pressure gas (generally nitrogen) that prevents oxidation of internal components and also increases the breakdown voltage across the outer bulb parts; (3) provides an inner surface that will accept phosphor coatings; and (4) normally acts as a filter, removing most of the UV radiation produced by the arc. Phosphors placed inside the outer envelope can convert some of this UV energy to light, as in fluorescent lamps.

Typically, the mercury lamp's inner envelope (arc tube) is made of fused silica with thin molybdenum ribbons sealed into the ends as current conductors. The outer envelope (bulb) is usually made of hard (borosilicate) glass but also can be of other glasses for special transmission or where pollution and thermal shock are not problems.

The essential construction details shown in Figure 6-57 are typical of lamps with fused silica (quartz) inner arc tubes within an outer envelope. Other lamps, such as those for special photochemical application and self-ballasted types, have different constructions.

The pressure at which a mercury lamp operates accounts in large measure for its characteristic spectral power distribution. In general, higher operating pressure tends to shift a larger proportion of emitted radiation into longer wavelengths. At extremely high pressure there is also a tendency to spread the line spectrum into wider bands. Within the visible region the mercury spectrum consists of five principal lines (404.7, 435.8, 546.1, 577, and 579 nm), which result in greenish-blue light at efficacies of 30 to 65 lm/W, excluding ballast losses. While the light source itself appears to be bluish-white, there is a deficiency of long-wavelength radiation, especially in low- and medium-pressure lamps, and most objects appear to have distorted colors. Blue, green, and yellow are emphasized; orange and red appear brownish. Clear mercury lamps generally have a CRI value of approximately 15, and are not desirable for use where people will occupy the space. They are, however, quite suited to landscape lighting (see Chapter 21, Exterior Lighting).

A significant portion of the energy radiated by the mercury arc is in the UV region. Through the use of phosphor coatings on the inside surface of the outer envelope, some of

this UV energy is converted to visible radiation. The most widely used lamps of this type are coated with a vanadate phosphor (4000 K, designation DX) that emits long-wavelength radiation (orange-red); this improves efficacy and color rendering. This phosphor also is blended with others to produce cooler or warmer colors. Figure 6-28 shows the spectral power distributions of a clear lamp and ones using these phosphors.

Metal Halide Lamps.⁵³⁻⁶¹ Metal halide lamps are similar in construction to mercury lamps, the major difference being that the metal halide arc tube contains various metal halides in addition to the mercury and argon. When the lamp attains full operating temperature, the metal halides in the arc tube are partially vaporized. When the halide vapors approach the high-temperature central core of the discharge, they are dissociated into the halogen and the metals, with the metals radiating their spectrum. As the halogen and metal atoms move near the cooler arc tube wall by diffusion and convection, they recombine, and the cycle repeats.

The use of metal halides inside the arc tube presents two advantages. First, metal halides are more volatile at arc tube operating temperatures than pure metals. This allows the introduction of metals with desirable emission properties into the arc at normal arc tube temperatures. Second, those metals that react chemically with the arc tube can be used in the form of a halide, which does not readily react with fused silica.

The efficacy of metal halide lamps is greatly improved over mercury lamps. Commercially available metal halide lamps have efficacies of 75 to 125 lumens/watt (excluding ballast losses). Almost all varieties of white-light metal halide lamps have color rendering properties as good as or superior to phosphor-coated mercury lamps.

The radiating metals introduced as halides in these lamps have characteristic emissions that are spectrally selective. Some metals principally produce visible radiation at a single wavelength, while others produce a multitude of discrete wavelengths. Still others provide a continuous spectrum of radiation. In order to obtain a desired spectrum, blends of metal halides are used. Two typical combinations of halides used are scandium and sodium iodides, and dysprosium, holmium, and thulium rare-earth (RE) iodides. Their spectral power distributions are shown in Figure 6-28. Other metals, such as tin, when introduced as halides, radiate as molecules, providing a continuous band spectra across the visible spectrum. The scandium-sodium system, for example, can produce CCTs between 2500 to 5000 K by varying the blend ratio and arc tube operating temperature. The rare-earth system, on the other hand, has a characteristic CCT of approximately 5400 K, which, when augmented by the inclusion of sodium iodide, may be lowered to 4300 K. A rare-earth system augmented with cesium and sodium iodides can achieve a CCT of 3000 K. The rare-earth system provides a somewhat higher general color rendering index than the scandium-sodium system; lithium iodide additions look

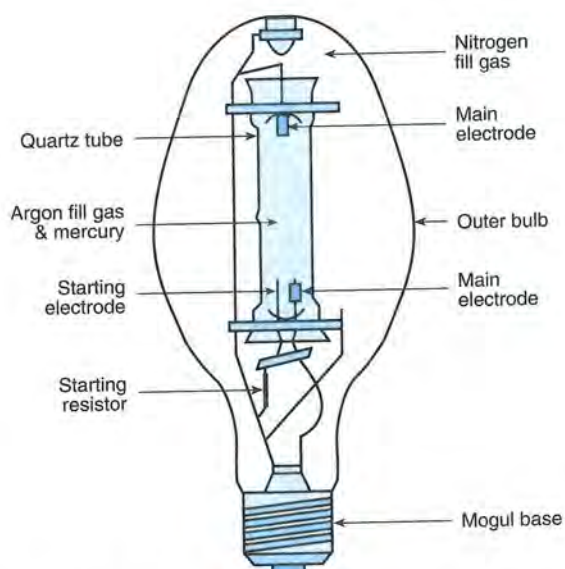


Figure 6-57. Mercury vapor lamp construction.

promising for enhancing the color rendering properties of the scandium-sodium system.

Selected colors also can be produced using single elements in the arc tube: sodium for orange, thallium for green, indium for blue, and iron for UV. Luminous efficacy and lamp life tend to be greater for scandium-sodium lamps, but thallium can be used to improve the efficacy of RE lamps. These trade-offs should be considered in selecting a lamp type for each particular application. Metal halide lamps are also available with phosphors applied to the outer envelopes (Figure 1-13). These phosphors lower the CCT of the lamps by approximately 300 K. The main use of the phosphor coating is to create a more diffuse light source.

Metal halide lamp construction is similar to that of a mercury lamp (Figure 6-58). One significant design characteristic is that the arc tubes usually are smaller for equivalent wattages. The metal halide arc tube has a white coating applied to the ends to increase vaporization of the metal halides.

Another design characteristic of metal halide lamps is that the arc tubes often are custom shaped. Most metal halide lamps are life- and lumen-rated in the vertical operating position. For instance, a universal operation lamp has its best performance in the vertical position. When a universal lamp is operated horizontally, the arc bows upward due to convection currents. At the same time, the metal halide pool (which is liquid) moves to the center of the arc tube. The bowed arc moves farther from the metal halides than when the lamp is vertical, causing them to cool. This lowers the vapor pressure of the metal halide chemicals and decreases

the concentration of metals in the arc with a resulting loss in light. In addition, the bowed arc moves closer to the top of the arc tube wall, causing its temperature to increase. The higher wall loading on the arc tube material results in a decrease in life rating by approximately 25%.

Since many applications require horizontal lamp orientation, a number of arc tube designs have been developed. There are two common configurations for horizontal high output arc tubes as shown in Figure 6-59. The first is a bowed arc tube shaped to follow the natural bowing of the horizontal arc. In this design, the chemicals are confined to the ends of the arc tube as the shape prevents migration. The second design is an asymmetric arc tube with the electrodes lower in the arc tube body such that the arc bows to the center line of the arc tube. Both of these designs provide increased light (approximately 25%) and longer life (approximately 33%) over the universal lamps operated horizontally.

Since the horizontal high-output arc tubes are designed to accommodate the upward bow of a horizontally operating arc, the arc tube must be operated horizontally to prevent overheating of the arc tube walls, which dramatically shortens lamp life and increases the probability of violent failures. A special base and socket are always used with horizontal high-output lamps to help ensure proper arc tube orientation (Figure 6-60). Lamp operating position is much less important for mercury and high-pressure sodium lamps.

Some arc tubes have been designed with ovoid shapes (Figure 6-61a). These arc tubes are actually formed in a mold using high-pressure gas. They are commonly referred to as formed body arc tubes. The older style of arc tubes are referred to as pinched body arc tubes (Figure 6-61b). The molding process ensures a highly repeatable and accurate shape for each arc tube. The actual contour and shape of the arc tube gives some excellent benefits in performance. The walls of the arc tube are contoured to better follow the shape of the arc, thereby allowing for a more uniform thermal profile for the arc tube. This shape also allows the metal halide chemicals to heat up more rapidly than those in the conventional pinched body arc tube. On average, formed body arc tubes warm up three times faster than pinched body arc tubes of the same wattage. Formed body arc tubes have much smaller pinch seal areas. These areas serve to cool the arc tube end chambers and thereby reduce lamp efficacy by lowering the temperature of the metal halide pool. This undesirable cooling is more of a problem in lower-wattage lamps in which the pinch seal area comprises a greater part of the total thermal mass of the arc tube than for the higher wattage lamps.

The smaller pinch seal area has an effect on lamp starting. The older pinch seal designs use a secondary starter electrode that helps to initiate breakdown of the arc tube gases. In formed body arc tubes, there is no room for the secondary electrode. Consequently the arc is initiated by a high-voltage pulse (typically 3,000 V minimum) applied directly across the main electrodes. Devices called ignitors are used to provide these starting pulses. Ignitor starting has

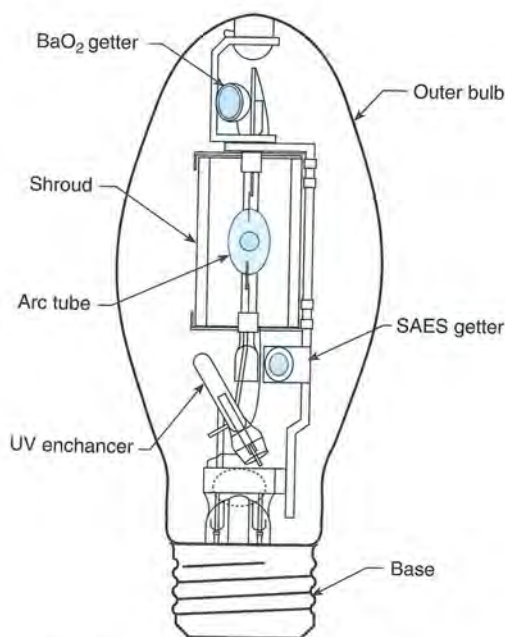


Figure 6-58. Metal halide lamp construction.

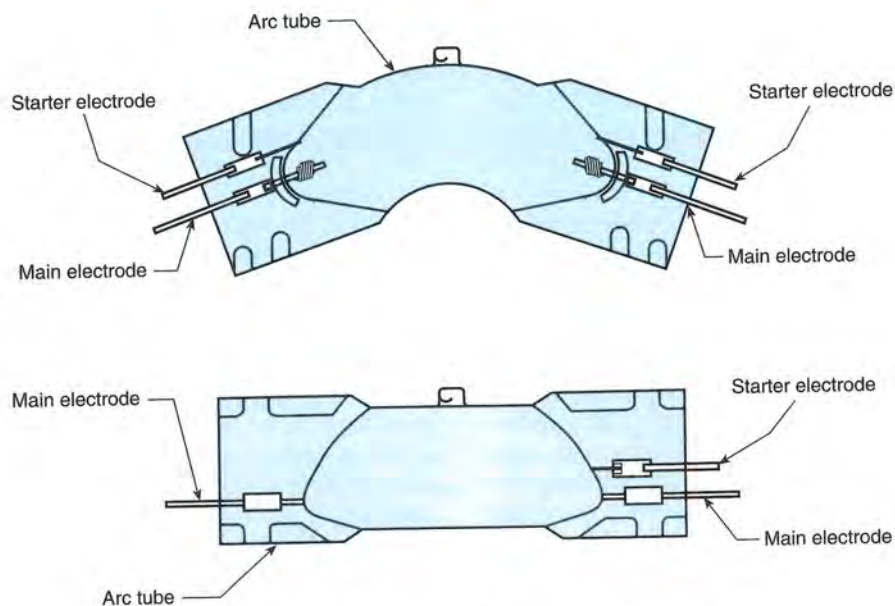


Figure 6-59. Common configurations for horizontal metal halide lamps.

been found to have additional performance features. In general, lamps start faster when ignitors are used. They start more reliably, and the fill pressure inside the arc tube can be increased over standard starter electrode systems. This higher fill pressure helps to retard tungsten evaporation from the electrode, which causes lumen depreciation due to arc tube wall darkening.

The classic pinched body metal halide lamps that use a starter electrode must also contain a system that provides for either shorting of the starter electrode to the main electrode or opening the starter electrode circuit after the lamps have started. This is required to prevent electrolysis in the fused

silica between the starting and operating electrodes, especially when a halide such as sodium iodide is used in the lamp. Failure to short or open the starter electrode circuit will result in very short lamp lives. These starter circuits typically use a bimetal switch. The location and type of switch

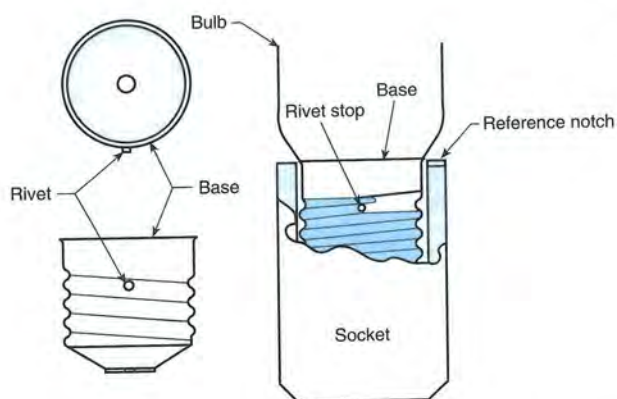


Figure 6-60. Base and socket configuration for some horizontal high-output metal halide lamps.

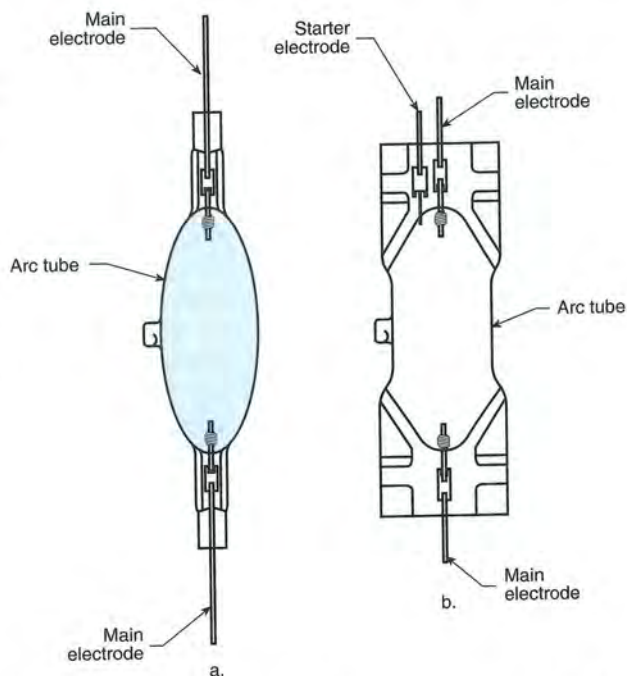


Figure 6-61. Common arc tubes: (a) ovoid, and (b) pinched body.

can restrict the lamp operating position as the bimetal must achieve a certain temperature to function.

In some metal halide lamps the electrical connection to the electrode at the dome of the lamps is made by a small nonmagnetic wire remote from the arc tube. This prevents diffusion of sodium through the arc tube by electrolysis caused by a photoelectric effect when the current lead is near the arc tube. Most metal halide lamps above 150 W require a higher open-circuit voltage to start than mercury lamps of corresponding wattage. Therefore, they require specific ballasts. Certain metal halide lamps designs, however, can be operated on some types of mercury ballasts in retrofit situations.

Most metal halide lamps use getters to overcome impurities that, if present in the outer jacket of a metal halide lamp in sufficient concentrations, can compromise performance. The predominant problems arise from hydrogen and carbon contamination.

Special metal halide lamps are available that automatically extinguish the arc should the outer envelope break or puncture. They can be used in locations where exposure to UV radiation should be avoided.⁶²

Low-wattage metal halide lamps⁶³⁻⁶⁵ (below 175 W) come in many varieties for different applications, such as displays, recessed lighting, and track lighting. They produce brilliant white light in a small arc capsule enclosed in a small outer jacket. Such lamps include single-ended lamps with medium or E27 bases (32 to 175 W), single-ended lamps with bipin bases (35 to 150 W), and double-ended lamps with recessed single contact bases (70 to 150 W).

Some single-ended lamps use a transparent sleeve surrounding the arc tube called a shroud. A thin-walled shroud is useful as a heat shield because it helps achieve a more uni-

form arc tube temperature; it also retards sodium loss. A heavy shroud is used in lamps suitable for open luminaires. These shrouds prevent the outer jacket of the lamp from breaking in case of an arc tube violent failure. When relamping an open luminaire it is important to use only open luminaire rated lamps (those with shrouds). To prevent user misapplication the industry has developed unique socket and base combinations for both medium and mogul base lamps.

Certain metal halide lamps must be operated in enclosed luminaires designed to contain any hot quartz fragments that might result from an arc tube rupture. Some metal halide lamps do not have a hard glass outer jacket. These lamps can have either no outer jacket or an outer jacket that is made from fused silica that transmits UV energy. In these designs, the luminaire must have a cover glass providing the UV filtration.

High-Pressure Sodium Lamps.⁶⁶ In high-pressure sodium lamps, light is produced by electric current passing through sodium vapor. These lamps are constructed with two envelopes, the inner arc tube being polycrystalline alumina, which is resistant to sodium attack at high temperatures and has a high melting point. Although translucent, this material provides good light transmission (more than 90%). The construction of a typical high-pressure sodium lamp is shown in Figure 6-62.

Polycrystalline alumina cannot be fused to metal by melting the alumina without causing the material to crack. Therefore, an intermediate seal is used. Either solder, glass, or metal can be used. Ceramic plugs also can be used to form the intermediate seal. The arc tube contains both xenon as a starting gas and a small quantity of sodium-mercury amalgam, which is partially vaporized when the lamp attains

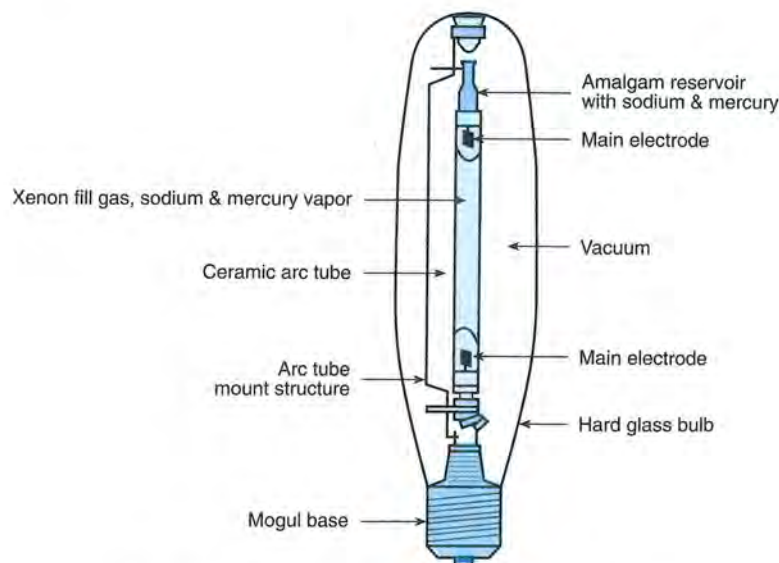


Figure 6-62. High-pressure sodium lamp construction.

operating temperature. The mercury acts as a buffer gas to raise the gas pressure and operating voltage of the lamp.

The outer borosilicate glass envelope is evacuated and serves to prevent chemical attack of the arc tube metal parts. It also helps to maintain arc tube temperature by isolating the metal from ambient temperature effects and drafts.

Most high-pressure sodium lamps can operate in any position. The operating position has no significant effect on light output. Lamps are also available with diffuse coatings on the inside of the outer bulb to increase source luminous size or reduce source luminance.

High-pressure sodium lamps radiate energy across the visible spectrum. This is in contrast to low-pressure sodium lamps, which radiate principally the doublet D lines of sodium at 589 nm. Standard high-pressure sodium lamps, with sodium pressures in the 5 to 10 kPa (40 to 75 Torr) range, typically exhibit color temperatures of 1900 to 2200 K and have a CRI of 22. At higher sodium pressures, above approximately 27 kPa (200 Torr), sodium radiation of the D line is self-absorbed by the gas and is radiated as a continuous spectrum on both sides of the D line. This results in the dark region at 589 nm as shown in the typical spectrum in Figure 6-28. Increasing the sodium pressure increases the CRI to at least 65 at somewhat higher correlated color temperatures; however, life and efficacy are reduced. White high-pressure sodium lamps have been developed with correlated color temperatures of 2700 to 2800 K and a CRI between 70 and 80. Higher-frequency operation is one method of providing white light at reduced sodium pressure. High-pressure sodium lamps have efficacies of 45 to 150 lm/W, depending on the lamp wattage and desired color rendering properties.

Because of the small diameter of a high-pressure sodium lamp arc tube, no starting electrode is included as in the mercury lamp. Instead, a high-voltage, high-frequency pulse is provided by an ignitor to start these lamps. Some special high-pressure sodium lamps use a specific starting-gas mixture (a combination of argon and neon that requires a lower starting voltage than either gas alone) and a starting aid inside the outer bulb. These lamps can start and operate on many mercury lamp ballasts.

High-pressure sodium lamps are also available with two identical arc tubes contained within the outer bulb. These arc tubes are connected in parallel inside the lamp, but only one arc tube is started with the ignitor pulse. In the event of a momentary power outage, this dual arc tube lamp restrikes immediately when power is restored. Within about one minute, the lamp returns to full light output.

Lamp Designations

The current identifying designations of high-intensity discharge lamps generally follow a system that is authorized and administered by ANSI. All designations start with a letter (H for mercury, M for metal halide, S for high-pressure sodium). This is followed by an ANSI-assigned number that

identifies the electrical characteristics of the lamp and ballast. After the number there are two letters that identify the size, shape, and finish of the bulb. After this sequence, the manufacturer may add special letters or numbers to indicate information not covered by the standard sequence of the designation, such as lamp wattage or color.

An example HID lamp designation is as follows:

M	57	PF	175/3K
(a)	(b)	(c)	(d)

- (a) HID type. "S" is for HPS lamps, "M" is for MH lamps, and "H" is for mercury lamps.
- (b) Electronic characteristics. For example, "57" is a 175-W MH lamp, "51" is a 400-W HPS lamp, "33" is a 400-W mercury lamp.
- (c) Bulb characteristics. For example, "PF" is a phosphor-coated ED bulb, "PE" is a clear ED bulb.
- (d) Additional characteristics. Many lamp manufacturers add additional (and often redundant) codes that more explicitly describe the wattage (175-W), color temperature (3000 K), or other special characteristics.

Lamp Starting

Mercury Lamps. Some special two-electrode mercury lamps, and many photochemical types, require a high open-circuit voltage to ionize the argon gas and permit the arc to strike. In the more common three-electrode lamps an auxiliary starting electrode placed near one of the main electrodes makes it possible to start the lamp at a lower voltage. Here, an electric field is first established between the starting electrode, which is connected to the opposite main electrode through a current limiting resistor, and the adjacent main electrode. This causes an emission of electrons, which develops a local glow discharge and ionizes the starting gas. The arc then starts between the main electrodes. The mercury gradually vaporizes from the heat of the arc and draws current. During this process the arc stream changes from the bluish glow of the argon arc to the blue-green of mercury, increasing greatly in luminance and becoming concentrated along the axis of the tube. At the instant the arc strikes, the lamp voltage is low. Normal operating values are reached after a warmup period of several minutes, during which the voltage rises until the arc attains a stabilization vapor pressure; the mercury is then entirely evaporated.

If the arc is extinguished, the lamp will not relight until it is cooled sufficiently to lower the vapor pressure to a point where the arc will restrike with the voltage available. The time from initial starting to full light output at ordinary room temperatures, with no enclosing lighting unit, and also the restriking time (the cooling time required before the lamp will restart), vary between 3 and 7 min, depending upon the lamp type.

Metal Halide Lamps. The method of starting most metal halide lamps above 150 W is through an auxiliary starter electrode similar to that used in mercury lamps. The presence of the metal halides causes the starting voltage to be higher than it needs to be for mercury lamps. Therefore, higher-wattage metal halide lamps generally are not operated on mercury control gear. Sometimes people operate 400-W metal halide lamps on standard mercury ballast. This is not good practice since aged lamps require higher starting voltages, if they start at all.

The newer formed body arc tubes do not have room to accommodate the starter electrode in the pinched body arc tube lamps (Figure 6-61b), and therefore a different method of starting is employed. These lamps use an ignitor, a high voltage–low current generating device, as part of the external control circuit. The ignitor provides enough voltage across the main electrodes to initiate an arc. Most lamps below 150 W use an ignitor for starting.

A metal halide lamp does not reach full light output immediately but instead must warm up over a period of several minutes (time to reach full light output is longer for higher lamp wattages). During this phase, the color of the discharge changes as the metal halides warm up, evaporate, and incorporate into the arc. Upon full warm up, the lamp color and electrical characteristics stabilize. Since a metal halide arc tube is smaller than that of a mercury lamp of equivalent wattage, it operates at a higher temperature. Hence, the time to cool down is longer and the time to reignite is longer. The hot restrike time in a conventional pinched body arc tube can be 15 min or longer. Lamps that use ignitor starting restrike much faster than the conventional pinched body arc tube designs with starter electrodes due to higher pulse voltages.

High-Pressure Sodium Lamps. Since the high-pressure sodium lamp does not contain a starting electrode, a high-voltage, high-frequency pulse is used to ionize the starting gas. Once started, the lamp warms to full light output in approximately 10 min, during which time the color changes.

Because the operating pressure of a high-pressure sodium lamp is lower than that of a mercury lamp, the restrike time is shorter. It usually restrikes in less than 1 min and warms up in 3 to 4 min (see also Figure 6-63).

Lamp Life and Lumen Depreciation

Average rated lamp life is defined as that time after which 50% of a large group of lamps are still in operation. The procedure prescribes operating cycles for HID lamps of 11 h on, 1 h off.⁶⁷ For certain lamp types and applications, criteria other than failure to light may be considered, such as rapid cycling, drastic color change, or significant reduction in lumen output. Lamp life is generally based on the prescribed operating cycle. HID lamp life and lumen maintenance are affected by changes in the operating cycle, however. As a rule of thumb, as the operating period is shortened by 50%, lamp life is reduced by approximately 25%. Contact lamp

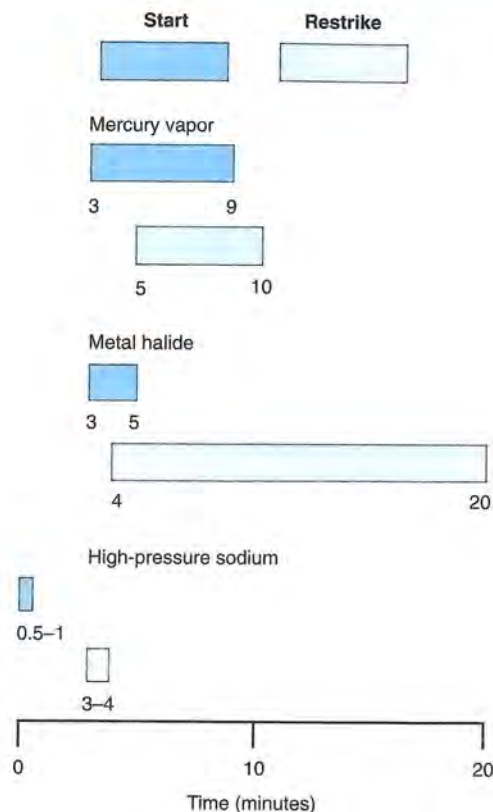


Figure 6-63. Starting and restrike times among different HID lamps.

manufacturers for further information about shorter operating cycles and reduced lamp life.

HID lamps usually are rated for initial lumens after 100 h of operation. Figure 6-64 illustrates light losses for three types of 400-W HID lamps over time.

Mercury Lamps. General-service mercury lamps have a long average rated life. They usually employ an electrode with a mixture of metal oxides embedded in the turns of tungsten coils from which the electrode is assembled. During the life of the lamp, this emission material is very slowly evaporated, or sputtered, from the electrode and is deposited on the inner surface of the arc tube. This process results first in a white deposit on the inner surface of the arc tube, eventually in a blackening of the arc tube, and ultimately in exhaustion of the emission material in the electrodes and the end of lamp life when the starting voltage exceeds the open-circuit voltage.

Metal Halide Lamps. Chemical reaction between the iodine in a metal halide lamp and the emission materials included in mercury lamp electrodes prevents the use of mercury electrodes in a metal halide lamp. Because the electrodes used with metal halide lamps evaporate more

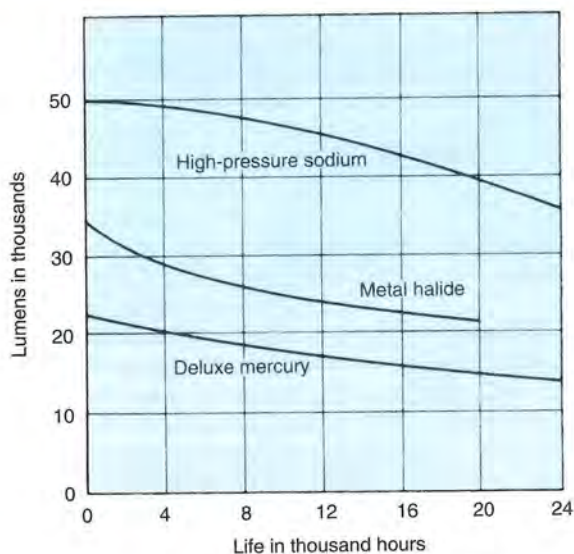


Figure 6-64. Typical lumen maintenance curves for 400-W high-intensity discharge lamps.

rapidly than mercury lamp electrodes, they generally have shorter life ratings. In addition, some metal halide lamps experience strong color changes toward the end of normal life. Where the color appearance of the lamps is critical, the useful life of the lamps ends when the color shift becomes objectionable.

High-Pressure Sodium Lamps. High-pressure sodium lamps employ electrodes very similar to those used in mercury lamps. This fact, combined with the smaller diameter of the arc tube, gives high-pressure sodium lamps excellent lumen maintenance.

The life of a high-pressure sodium lamp is limited by a slow rise in operating voltage that occurs over the life of the lamp. This rise is principally caused by arc tube end blackening from electrode sputtering. The blackening absorbs radiation, which heats up the arc tube ends and vaporizes additional sodium amalgam. This increases the arc tube pressure and consequently the arc voltage. Other reasons for arc tube voltage rise are the diffusion of sodium through the arc tube end seals and the removal of sodium from the arc stream by combination with impurities in the arc tube.

When the ballast can no longer supply enough voltage to reignite the arc during each electrical half-cycle, the lamp extinguishes. When it cools down, the lamp will again ignite and warm up until the arc voltage rises so that the ballast cannot support the arc. This cycling process occurs until the lamp is replaced.

Effect of Ambient Temperature

The light output of a typical double-envelope HID arc tube is little affected by the ambient temperature. These lamps

are generally satisfactory for temperatures down to -29°C (-20°F) or lower. On the other hand, single-envelope lamps, intended primarily for use as UV sources, are critically affected by low temperatures, particularly if the surrounding air is moving. They are not considered suitable for use below 0°C (32°F) without special protection, since they do not give full output. Ambient temperature affects the striking voltage of all discharge lamps, and in some cases higher starting voltages for indoor use are recommended for roadway and floodlighting installations in cold climates. Ballasts for roadway lighting service and other low-temperature applications are designed to provide the necessary voltage to start and operate each particular lamp at temperatures as low as -29°C (-20°F). Recommendations for starting voltages have been developed by ANSI.⁶⁸

Lamp Operating Temperature

Excessive envelope and base temperatures may cause failures or unsatisfactory performance due to softening of the glass, damage to the arc tube by moisture driven out of the outer envelope, softening of the basing cement or solder, or corrosion of the base, socket, or lead-in wires. Maximum bulb and base temperatures are prescribed by various standards associations. The use of reflecting equipment that concentrates heat and energy on either the inner arc tube or the outer envelope should be avoided. In the case of metal halide and high-pressure sodium lamps in which all the material is not vaporized, concentrated heat on the arc tube can affect the color of illumination as well as electrical characteristics and lamp life.

Flicker and Stroboscopic Effect

The light output of all HID lamps varies to some degree with cyclic changes of the line voltage. This flicker depends on the lamp type and the ballast circuit. Flicker can be an important consideration for HID lamps. In many lighting applications the stroboscopic effect from HID sources is not a problem. It can, however, be annoying to spectators in games such as tennis or Ping-Pong. Operators of rotating machinery can find it distracting. To minimize the stroboscopic effect, systems with a flicker index of 0.1 or less are suggested, or luminaires can be wired alternately on different phases of a three-phase system.

Figure 6-65 illustrates the variation in flicker index for mercury, metal halide, and high-pressure sodium lamps for several ballast types operated at 60 Hz. The flicker index is considerably higher in 50-Hz power systems. The flicker effect can be effectively eliminated by using electronic ballasts having high-frequency or rectangular wave characteristics.

In addition to the above, some flicker sometimes can be seen from the end of the lamp when viewed peripherally by the retina (see Chapter 3, Vision and Perception). This flicker is a result of the arc being initiated at alternate electrodes during positive and negative half cycles, and has a

Figure 6-65. Flicker Index for HID Lamps Operated on Different Ballast Types

Lamp type	Ballast	Flicker Index
Mercury		
250W Warm Deluxe	Reactor	.127
250W Cool Deluxe	Reactor	.137
250W Deluxe White	Reactor	.131
250W Deluxe White	CWA (M-H type)	.172
100W Deluxe White	CW-Premium	.142
100W Deluxe White	CW	.183
400W Deluxe White	Reactor	.121
400W Deluxe White	CWA (M-H type)	.144
High Pressure Sodium		
250W Deluxe	Reactor or CWA	.131
250W Standard	Reactor or CWA	.200
Metal Halide		
250W High Color Quality	Reactor	.080
250W High Color Quality	HPS-CWA	.102
175W Coated	CWA	.083
175W Clear-Vertical	CWA	.078
175W Clear-Horizontal		.092
250W Coated (A)	CWA	.070
250W Clear-Vertical	CWA	.102
250W Clear-Horizontal		.121
250W Coated (B)	CWA	.092
250W Clear-Vertical	CWA-Premium	.088
250W Clear-Horizontal		.097
400W Clear-Vertical	CWA	.086
400W Clear-Horizontal		.095
1000W Clear (vert)	CWA	.067
175W (3200K)	CWA	.090

frequency that is equal to line frequency. It is also eliminated in high-frequency operation.

Auxiliary Equipment

HID lamps have negative volt-ampere characteristics, and therefore a current-limiting device, usually in the form of a transformer and reactor ballast, must be provided to prevent excessive lamp and line currents. The lamps are operated on either multiple or series circuits. Figure 6-66 gives schematic diagrams of several typical ballast types. Figure 6-67 summarizes the characteristics of the most common combinations of HID lamps and ballasts.

A distinction must be made between lag circuit and lead circuit ballasts. The lamp current control element of a lag circuit ballast consists of an inductive reactance in series with the lamp. The current control element in lead circuit ballasts consists of both inductive and capacitive reactances in series with the lamp; however, the net reactance of such a circuit is capacitive in mercury and metal halide ballasts, and inductive in high-pressure sodium ballasts.

There are a number of ballasts in use for operating mercury lamps. Wattage losses in ballasts are usually in the order of 5 to 15% of lamp wattage.

Lag Reactor. The simplest lag circuit ballast is a reactor consisting of a single coil wound on an iron core placed in series with the lamp. The only function of the reactor is to limit the current delivered to the lamp. Such a reactor can be used only when the line voltage is within the specified lamp starting voltage range. The power factor of this circuit is approximately 50% lagging; this is commonly referred to as normal or low power factor. The line current under starting conditions is approximately 50% higher than normal operating current; therefore, it is recommended that supply wiring be sized for approximately twice the normal operating current.

High-power-factor versions are available where a capacitor is installed in the circuit to increase the power factor of the system to better than 90%. This is generally the preferred system, since it also reduces the input current under starting and operating conditions almost 50% below that of the low-power-factor system, allowing full utilization of the circuit.

Since a lag reactor performs only the function of current control, it is the smallest, most economical, and most efficient ballast. However, it has shortcomings that should be considered in application. The reactor provides little regulation for fluctuations in line voltage; for example, a 3% change in line voltage can cause a 6% change in lamp wattage. Therefore, the reactor is not recommended where line fluctuations exceed 5%.

High-Reactance Autotransformer. Where the line voltage is below or above the specified lamp starting voltage range, a transformer is used in conjunction with the reactor to provide proper starting voltage. This normally is accomplished with the combination of primary and secondary coils forming a one-piece single high-reactance autotransformer. The power factor of this circuit is approximately 50% lagging and has the same advantages and shortcomings as the normal power factor of a reactor lag circuit. High-power-factor versions are available in which a capacitor is installed in the circuit to increase the power factor of the system to better than 90%. The effect on input current is the same as in the high-power-factor reactor. Regulation and lamp performance are unchanged.

Constant-Wattage Autotransformer (CWA). This type of lead circuit ballast is the most widely used in mercury lighting systems. It consists of a high-reactance autotransformer with a capacitor in series with the lamp. The capacitor allows the lamp to operate with better wattage stability when the voltage on the branch circuit fluctuates. This ballast is used when line voltage is expected to vary by more than 5%. For example, a 10% change in line voltage would result in only a 5% change in lamp wattage. Other advantages with the CWA ballast are high power factor, low line extinguishing voltage, and line starting currents that are lower than normal line currents. The CWA ballasts allow for maximum loading on branch circuits and provide an economical and efficient mercury lighting system.

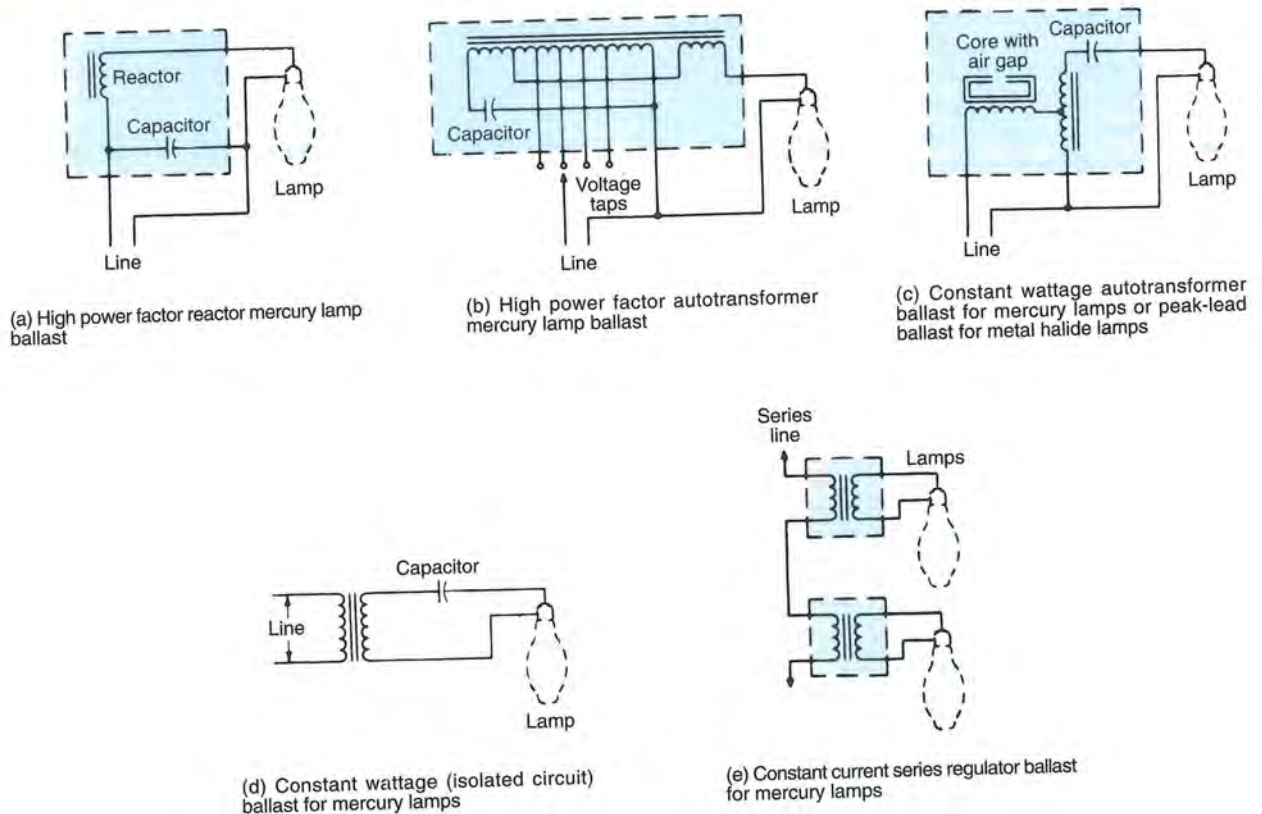


Figure 6-66. Typical circuits for operating high-intensity discharge lamps.

Figure 6-67. Characteristics of Common Combinations of HID Lamps and Ballasts

Ballast/lamp	Input Power (watts)	Ballast Factor	Efficacy (lumens/watt)	Power Factor	Current THD
Ballast for 70-W metal halide lamp	95	1	58	≥ 0.9	$\leq 30\%$
Electronic ballast for 70-W metal halide lamp	82	0.95	64	≥ 0.9	$\leq 30\%$
Ballast for 400-W metal halide lamp	458	1	79	≥ 0.9	$\leq 30\%$
Ballast for 70-W high pressure sodium lamp	94	1	68	≥ 0.9	$\leq 30\%$
Ballast for 250-W high pressure sodium lamp	300	1	87	≥ 0.9	$\leq 30\%$
Ballast for 175-W mercury vapor lamp	205	1	39	≥ 0.9	$\leq 30\%$

The capacitor used with the CWA ballast performs an important ballasting function, as in all lead-type circuits. The capacitor used in lag-type high-power-factor reactor and high-power-factor autotransformer ballasts is purely a power factor correction component and has no ballasting function.

Constant Wattage (CW). This type of ballast, also referred to as regulated or stabilized, has operating characteristics similar to the CWA. The light output and wattage vary less than 2% with up to a 13% change in line voltage. The CW ballast, like the CWA ballast, uses a lead circuit; it differs in that the lamp circuit is completely isolated from the primary winding. It also has the same advantages as the CWA ballast, such as high power factor, low line extinguishing voltage, and low line starting currents.

Two-Lamp Lead-Lag Circuit. The lead-lag ballast design approach is commonly used to operate two 250-, 400-, or 1000-W mercury or metal halide lamps in two independent circuits. A current-limiting reactor operates one lamp, and a combination reactor and capacitor connected in series operates the second. The lamps operate independently, so that the failure of one has no effect on the other. The input current of the combination of capacitors and reactors is lower than the sum of the two individual operating currents. These elements provide a high power factor and reduce flicker.

This circuit can be used only when the line voltage is within the specified lamp starting voltage range. It is the most economical two-lamp system with regulation similar to the normal-power-factor reactor and autotransformer ballasts. A lag reactor may be used in one luminaire and a lead reactor in the next luminaire. An equal number of each in a branch circuit will result in a high branch circuit power factor.

Two-Lamp Series (Isolated) Constant Wattage. This circuit is essentially the same as single-lamp constant wattage, except that it operates two lamps in series. The most effective use of this circuit is in applications where the ambient temperature is -18°C (0°F) or above. It is most popular for indoor 400-W applications.

Constant-Current Series Regulators. Mercury lamps also are operated in series on constant-current series regulators. The most commonly used method employs a current transformer for each lamp. It differs in design from the more common multiple type of ballast. The usual design is a two-winding transformer as illustrated in Figure 6-66e. Since the series circuit regulator reactance limits the current in the circuit, the individual lamp current transformer is not designed to limit current, but rather to transform it from the regulator secondary current to the rated lamp current. In addition, the transformer is made to limit the secondary open-circuit voltage so that no cutout is necessary when a lamp fails. Series transformers are available for the more popular lamps to operate from either 6.6-, 7.5- or 20-A series circuits and can be operated on all types of constant-current transformers. These circuits usually are satisfactory for metal halide lamps and high-pressure sodium lamps designed for operation on reactor-type mercury ballasts.

Two-Level Mercury Ballasts. Two-level operation of mercury lamps can be accomplished by switching capacitors on lead circuit ballasts. Such ballasts that operate 125-, 250- and 400-W mercury lamps at two levels are available. For example, a 400-W mercury lamp may be operated at either 400 or 300 W by switching leads at the ballast. These two-level mercury ballasts are used for energy saving. Similar designs are available for high-pressure sodium and metal halide lamps. Both lamp manufacturer and ballast manufacturer should be contacted for specific information.

This control technique is presently limited to horizontal operation above 10°C (50°F). The warmup time is 50% longer on low level.

Metal Halide Lamps. Metal halide lamps operate well on many different types of control gear. The control gear selection depends on the operating environment of the lamp and the degree of voltage regulation provided by the local utility. In the United States, the common type of control gear for lamps over 150 W is the lead peaked autotransformer. This control gear provides moderately good voltage regulation, yielding a change in lamp wattage of 7 to 10% for a line voltage change of 10%. The lead peaked autotransformer

performs much like the CWA ballast and has similar operating features. In Europe and many other countries where high open-circuit voltages are available from the mains, lag-reactor ballasts plus an ignitor are more commonly used. Where voltage regulation is good, the use of lag-reactor ballasts can save significant energy over the more common multi-tap lead peaked autotransformer.

For metal halide lamps below 175 W, the most common control gear is the lag reactor or high-reactance autotransformer. Power correcting capacitors typically are employed. Using the lag reactor ballast to regulate lamp wattage causes the least line voltage variations. A 5% change in line voltage can result in a 12% change in lamp wattage. Long-term operation of lamps under high line conditions shortens lamp life. For starting, an ignitor is used that provides a high voltage-low current pulse of between 3 and 5 kV. There are three types of ignitors in use today. The most common is the impulser or parallel ignitor, which uses a ballast winding as the ignitor's pulse transformer. Another type is the superimposed or series ignitor, which contains a pulse transformer that is independent of the ballast windings. Finally, there is the two-wire ignitor, which provides a lower pulse voltage directly across the lamp leads.

High-Pressure Sodium Lamps. Unlike mercury and metal halide lamps, which exhibit relatively constant lamp voltage with changes in lamp wattage, the high-pressure sodium lamp voltage varies with lamp wattage. Therefore, operating parameters for maximum and minimum permissible lamp wattage and voltage have been established.⁶⁶ The latest ANSI recommendations for high-pressure sodium lamps should be followed. Figure 6-68 shows the lamp voltage and wattage limits for 400-W high-pressure sodium lamps.

Lag or Reactor Ballast. This ballast type is similar to the mercury lamp reactor ballast. It is a simple reactor in series

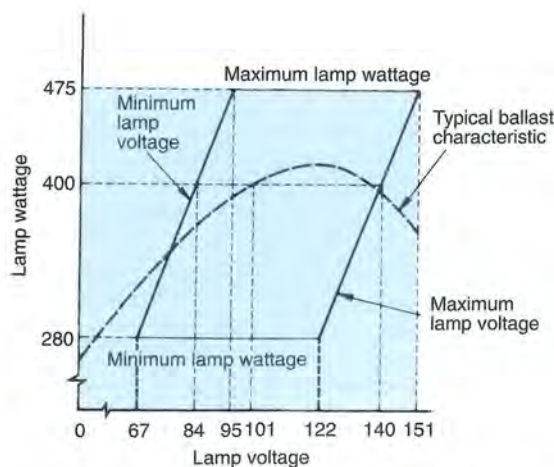


Figure 6-68. Wattage and voltage limits for 400-W high pressure sodium lamps.

with the lamp, designed to keep the operating characteristics within the trapezoid. A starting circuit is incorporated to provide the starting pulse. Step-up or step-down transformers are provided where necessary to match the line voltage. In most cases, a power-factor-correcting capacitor is placed across the line or across a capacitor winding on the ballast primary. This type of ballast usually provides good wattage regulation for variations in lamp voltage, but rather poor regulation for variations in line voltage. It is the least costly ballast with the lowest power loss among ballasts for high-pressure sodium lamps.

Magnetic Regulator or Constant-Wattage Ballast. This ballast consists essentially of a voltage-regulating section that feeds a current-limiting reactor and the pulse starting circuit. It provides good wattage regulation for changes in line voltage, as a result of the voltage-regulating section, and good regulation for changes in lamp voltage, which is the main characteristic of the reactor ballast.

The magnetic regulator is a high-cost ballast, having the greatest power losses, but it generally provides good wattage regulation under all conditions of line and lamp voltage. A power-factor-correcting capacitor usually is included. It should be noted that this circuit differs from constant-wattage mercury ballast circuits.

Lead Circuit Ballast. This circuit is similar to that of the CWA mercury-lamp ballast. It operates with a combination of inductance and capacitance in series with the lamp. It differs in design from the CWA mercury-lamp ballast in that it does not maintain a constant lamp current but rather decreases the current as the lamp voltage increases, so as to keep the lamp operating wattage within the trapezoid limits. This ballast type provides wattage regulation for changes in both line voltage and lamp wattage. For a change of no greater than 10% in line voltage it maintains the lamp wattage within the trapezoid. It is intermediate in cost and power losses.

Ignitors. Ignitors are used in the ballast circuit for most high-pressure sodium lamps, some metal halide lamps and some specialty arc lamps. The ignitor starts cold lamps by first providing a high enough voltage for ionization of the gas to produce a glow discharge. To complete the starting process, enough power must then be provided by the starting pulses to sustain an arc through a glow-to-arc transition. The range of pulse voltages to start cold lamps is 1 to 5 kV, usually provided by an electronic resonant circuit which applies multiple pulses to the lamp when the circuit is energized. The circuit turns itself off after the lamp starts by sensing the reduction in open-circuit voltage or, with some ignitors, after a fixed period of time.

Instant restarting of hot lamps is accomplished by increased ignition voltage. Voltage pulses of 10 to 70 kV are required by most HID lamps, and these are provided by resonant circuits. To halve the voltage to ground values, ignitor

circuits are available to apply opposing pulses simultaneously to the ends of the lamp. Most instant-restart lamps are of double-ended construction to minimize arc-over between lead wires, internal supports, or base contacts. These high-voltage starting pulses normally are applied in one or several short bursts, using the open-circuit voltage reduction on restart to turn off the ignitor.

Dimming of High-Intensity Discharge Lamps

Although HID lamps are optimized to operate at full power, some energy savings can be obtained through dimming. In energy management applications, savings of 50% or more might be obtained where available daylight is used with a photosensor and dimming control system. Daylight tends to compensate for the color changes of dimmed HID lamps. Additional controls for HID lighting can be employed for lumen maintenance and with time-of-day and demand reduction programs as administered by a computer or a simple time clock. Simple manual control for an HID dimming system can provide flexibility in multipurpose room applications and improved efficiency by tuning the light output for a specific task (see Chapter 27, Lighting Controls).

Some light sources are more suitable for dimming than others. Therefore, when considering a particular HID light source for dimming, it is suggested that the manufacturers of the lamp and the dimming system be contacted for information or performance characteristics in the dimmed state. In some cases, the lamp manufacturer's warranty is limited when dimming. In a properly designed dimming system, however, lamp life is unaffected by dimming.

The slow warmup and hot restrike delay, which are characteristic of HID sources, also apply to dimming. HID lamps respond to changes in dimmer settings much more slowly than incandescent or fluorescent sources; delays between minimum and maximum light output vary 3 to 10 min. Instantaneous dimming is available, however, over a limited range for some lamps.

HID lamps should be started at full power and the dimming delayed until the lamp is fully warmed up. Properly designed dimming systems ensure this occurs.

In addition to speed, the range of response is not comparable to that of incandescent or fluorescent dimming; however, in most cases the lamp efficacy and color are reasonably good down to 50% dimming or less. While not well suited to dramatic lighting or theatrical effects, they are quite satisfactory for many energy management applications. In these applications, the slow response of HID lamps provides additional system stability and minimal occupant distraction.

Typical curves of lumen output versus input power are shown in Figure 6-69. These curves describe general trends; the dimming system manufacturer should be consulted for more details.

Clear mercury lamps change very little in color from 100

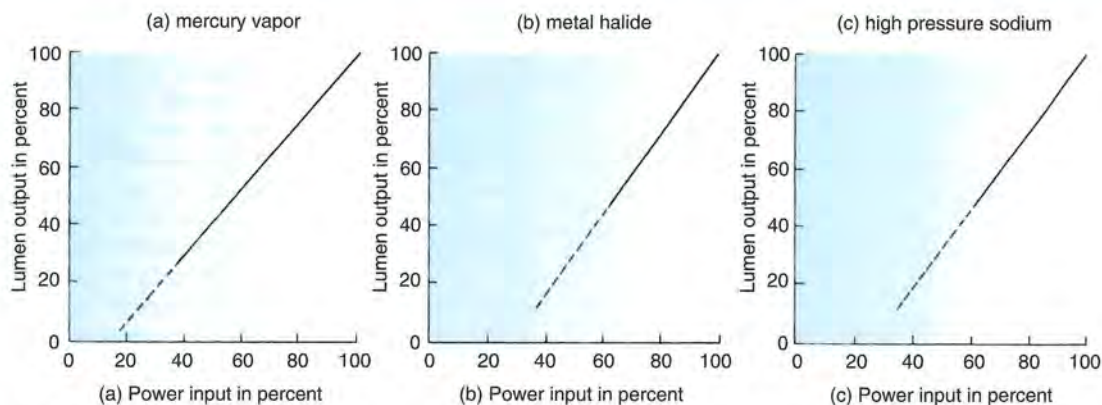


Figure 6-69. Lumen output vs. power input for high-intensity discharge lamps: (a) mercury vapor, (b) metal halide, and (c) high-pressure sodium. The dotted lines represent operating areas where significant color changes in the lamp occur.

to 25% light output; the blue-green color that is characteristic of clear mercury sources is present at all dimmer settings (Figure 6-70). Color-improved mercury lamps generally perform well down to approximately 30% light output.

The color appearance, color consistency from lamp to lamp, and color rendering of some clear, low-wattage metal halide lamps can begin to change at 80% lumen output. For higher wattages, the color of the clear lamps begins to change at approximately 60% light output, where a blue-green color (characteristic of mercury vapor) starts to appear. The effect is somewhat less with phosphor-coated lamps.

The color appearance of typical high-pressure sodium lamps does not appreciably change until approximately 50% light output. Below 50%, a strong yellow color, characteristic of low-pressure sodium, begins to prevail. In the case of the higher-color-rendering high-pressure lamps, the lamp manufacturer should be consulted on dimming performance.

Self-Ballasted Lamps

Self-ballasted mercury lamps are available in various wattages. These lamps have a mercury vapor arc tube in series with a current-limiting tungsten filament. In some types, phosphors coated on the outer envelope provide additional color improvement. The overall efficacy is lower than that of other mercury lamps because of the resistive losses of the tungsten filament. As the name denotes, these lamps do not require an auxiliary ballast.

SHORT-ARC LAMPS

Short-arc or compact-arc lamps characteristically provide a source of very high luminance. They are primarily used in searchlights, projectors, display systems and optical instru-

ments (e.g., spectrophotometers and recording instruments) and for simulation of solar radiation. They also can be used as sources of modulated light, generated through current modulation.

Short-arc lamps are high-pressure gas discharge lamps characterized by an electrode-stabilized arc that is short compared with the size of the envelope. Depending on rated wattage and intended application, their arc length may be from about 0.01 to 0.47 in. (0.3 to 12 mm). These arcs have the highest luminance and radiance of any continuously operating light source and are the closest to being a true point source.⁶⁹⁻⁸²

Some typical short-arc lamps are shown in Figures 6-71 and 6-72. These lamps have optically clear fused silica (quartz) bulbs of spherical or ellipsoidal shape with two diametrically opposite seals. Four types of seal are used in short-arc lamps. The graded seal and the molybdenum foil seal are current-carrying seals, while the molybdenum-and-Kovar cup seal and the elastomer (mechanical) seal are separated from the current conductor by a cup or a flange. For applications requiring ozone-free operation, the lamp envelopes are fabricated from quartz, which does not transmit wavelengths below 210 nm.

Most short-arc lamps are designed for dc operation. The better arc stability and substantially longer life of the dc lamps have limited the use of ac short-arc lamps to special applications.

Starting of Short-Arc Lamps

Like most vapor discharge lamps, short-arc lamps require auxiliary devices to start the arc and limit the current. For ac lamps, either resistive or inductive ballasts are used. Direct-current lamps are best operated from specifically designed power systems that provide, with good efficiency, the high-voltage pulses (up to 50 kV) required to break down the gap between the electrodes, ionize the gas, and heat the cathode

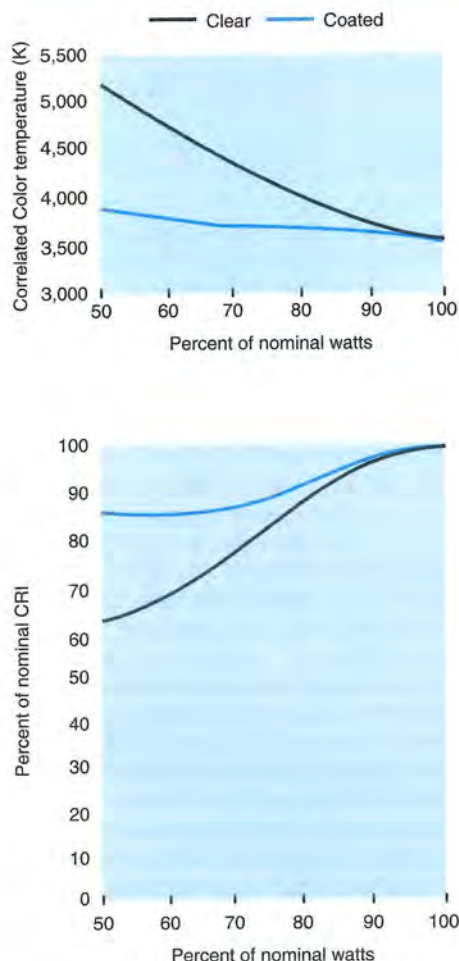


Figure 6-70. Correlated color temperature and CRI shift with dimming. Clear metal halide lamps can experience a shift in color temperature of over 1000 K and a drop of 35% in CRI when dimmed to 50% of rated output. Phosphor-coated lamps are much less vulnerable to this color shift.

tip to thermionic emitting temperatures. Further, they provide enough open-circuit dc voltage to assure the transition from the low-current, high-voltage spark discharge initiated by the starter to the high-current, low-voltage arc. With a properly designed system, a short-arc lamp will start within a fraction of a second. Many power supplies are regulated so that lamp operation is independent of line voltage fluctuation. Four basic types of sensors for power regulation are presently in use: current, voltage, power, and optical regulators. The type of power system used depends on the specifics of the application.

Mercury and Mercury-Xenon Lamps^{69,70,72,76}

To facilitate lamp starting, short-arc mercury lamps contain argon or another rare gas at pressures of 1 to 4 kPa (0.15 to

0.58 lb/in.²), the same as standard mercury lamps. After the initial arc is struck, the lamp gradually warms up, and the voltage increases and stabilizes as the mercury is completely vaporized. Mercury lamps require several minutes to achieve full operating pressure and light output. This warmup time is reduced by approximately 50% if xenon at greater than atmospheric pressure is added to the mercury. Lamps with this type of fill are known as mercury-xenon short-arc or compact-arc lamps. The spectral power distribution in the visible region is essentially the same for both types, consisting mainly of the five mercury lines and some continuum due to the high operating pressure (Figure 6-73). The luminous efficacy of these lamps is approximately 50 lm/W at 1000 W and approximately 55 lm/W at 5000 W. Mercury and mercury-xenon lamps are available from 30 to 7000 W and are usually operated in the vertical position.

Xenon Lamps^{71,74-82}

Xenon short-arc lamp are filled with several atmospheres of xenon gas. They reach 80% of the final output immediately. The CCT of the arc is approximately 5000 K. The spectrum is continuous from the UV through the visible into the infrared (Figure 6-74). Xenon lamps exhibit strong emission lines in the near infrared between 800 and 1000 nm and some weak lines in the short-wavelength visible region.

Xenon short-arc lamps range from 5 to 32,000 W, and they are available for operation in vertical or horizontal positions. Lamps designed for operation above 10 kW typically require liquid cooling of the electrodes. The luminous efficacy of the xenon short-arc lamp is approximately 30 lm/W at 1000 W, 45 lm/W at 5000 W, and over 50 lm/W at 20 kW and above.

Ceramic Reflector Short-Arc Xenon Lamps

Ceramic reflector xenon (CRX) lamps combine the basic technology of short-arc lamps and an internal reflector that focuses the arc's energy through a sapphire window in the ceramic-to-metal housing. The window transmits energy in both the IR and UV regions of the spectrum. These devices have the advantages of increased output, safety, and ease of handling and installation. They also obviate some peripheral equipment such as optical focusing components needed in many applications where short-arc lamps are used. CRX lamps are available with inputs from 175 to 1000 W. Their spectral power distributions can be varied for special applications by altering the reflector material or its coating.

Lamp Operating Enclosure

Short-arc mercury, mercury-xenon, and xenon lamps are under considerable pressure during operation (up to 5000 kPa [726 lb/in.²] for small lamps and approximately 1000 kPa [145 lb/in.²] for large ones) and therefore must be enclosed during operation. In addition, precaution must be taken to

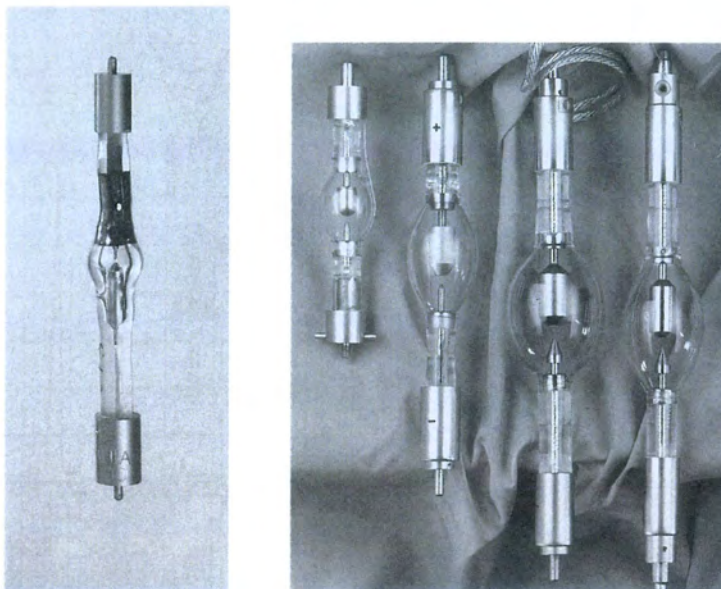


Figure 6-71. Typical short-arc lamps: (a) low-wattage mercury-argon lamps (100-W at left, 200-W at right), and (b) medium-wattage xenon lamps (from left: 1.6, 2.2, 4.2, 3.0 kW).

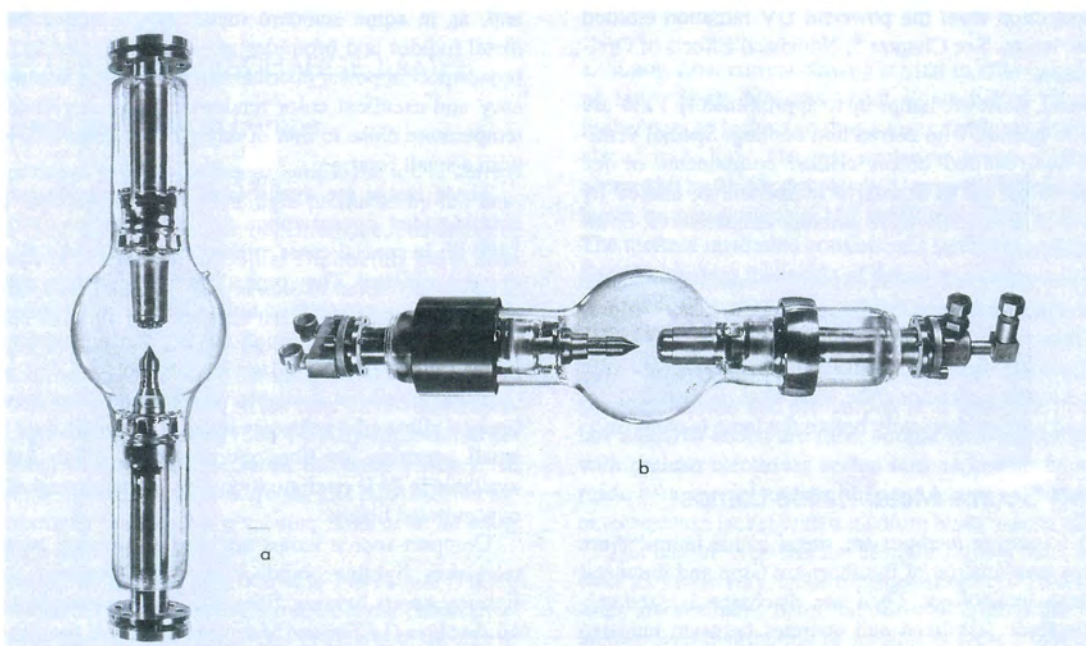


Figure 6-72. Typical high-power xenon compact arc lamps with liquid-cooled electrodes: (a) 30-kW lamp for solar simulators (principal operating position is vertical), and (b) 20-kW lamp for military searchlights (principal operating position is horizontal).

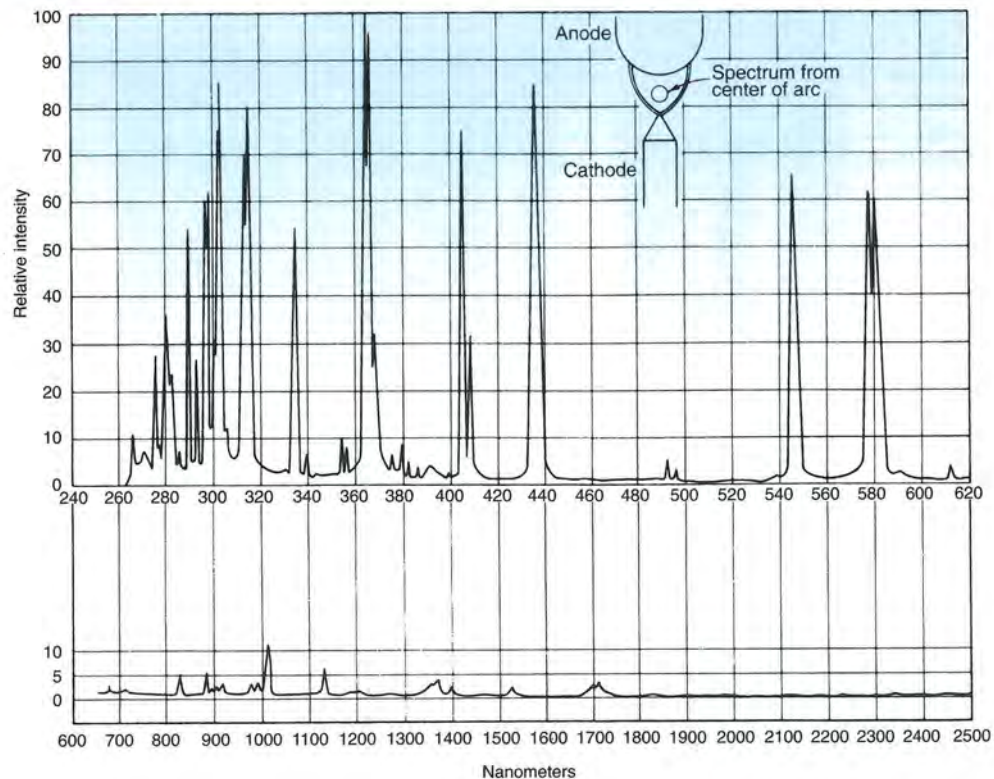


Figure 6-73. Spectral power distribution of a 2.5-kW mercury-xenon lamp from 240 to 2500 nm.

ensure protection from the powerful UV radiation emitted from these lamps. See Chapter 5, *Nonvisual Effects of Optical Radiation*.

In general, short-arc lamps up to approximately 1 kW are designed to operate with convection cooling. Special ventilation is not required unless critical components of the lamps are subjected to excessive temperatures, caused by confined enclosures, excessive ambient temperatures, or infrared radiation.

For safety during shipment, storage, or handling of xenon or mercury-xenon lamps, special protection cases are provided. These cases are made of metal or plastic and are so arranged around the bulb that the lamp can be electrically connected without removing the case. The case should not be removed until immediately before the lamp is energized.

Compact-Source Metal Halide Lamps

Compact-source, or medium-arc, metal halide lamps^{83,84} are based on a combination of the short-arc lamp and the metal halide lamp technology. Their arc discharge is predominantly electrode stabilized and operates between tungsten electrodes spaced 2.5 to 35 mm (0.1 to 1.4 in.) apart in ellipsoidal or almost spherical quartz bulbs. They are filled with mercury and argon as basic elements for starting the arc,

and, as in some standard metal halide lamps, rare-earth metal iodides and bromides are added in order to obtain a broad spectral power distribution. Both a high luminous efficacy and excellent color rendering with a correlated color temperature close to that of daylight are achieved, together with a small source size.

These lamps are available in various single-ended and double-ended constructions typically ranging from 70 to 1800 W. In special cases, higher wattages (up to 18,000 W) may be achieved. They typically are designed to operate on alternating current and require unique power supplies or ballasting equipment with high-voltage starting devices. Most lamps can be instantly restarted when hot.

Some lamps are available with the arc tubes mounted in integral ellipsoidal reflectors that can focus the light through small apertures or fiber-optic bundles. Other lamps are available in PAR configurations for applications that require concentrated beams.

Compact-source lamps are used for motion picture and television lighting, outdoor location lighting, theatrical lighting, sports lighting, fiber-optic illuminators, liquid crystal displays (LCD), and video projectors. If used in projectors, careful attention must be given to the modulation of the lamp output and the projector's shutter speed (frame rate) to avoid unintentional stroboscopic effects.

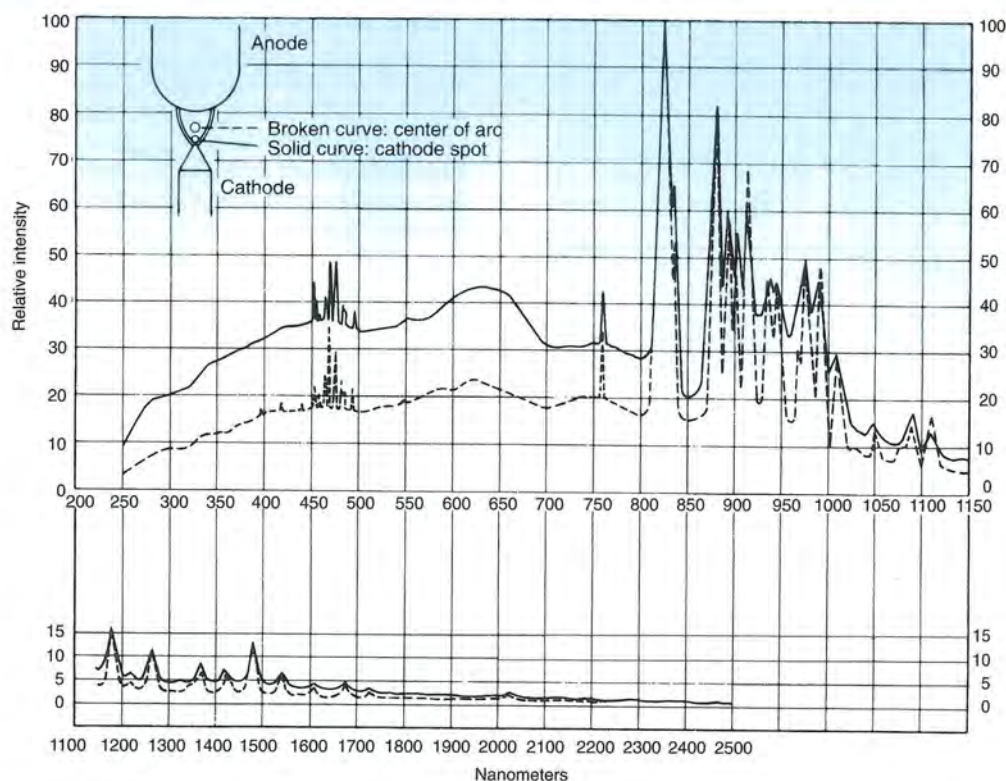


Figure 6-74. Spectral power distribution of a 2.2-kW xenon lamp from 200 to 2500 nm.

MISCELLANEOUS DISCHARGE LAMPS

Low-Pressure Sodium Lamps

In low-pressure sodium discharge lamps, the arc is carried through vaporized sodium. The light produced by the low-pressure sodium arc is almost monochromatic, consisting of a double line at 589.0 and 589.6 nm. The starting gas is neon with small additions of argon, xenon, or helium. In order to obtain the maximum efficacy of the conversion of the electrical input to the arc discharge into light, the vapor pressure of the sodium must be approximately of 0.7 Pa ($1/10^{-4}$ lb/in.²), which corresponds to an arc tube bulb wall temperature of approximately 260°C (500°F). Any appreciable deviation from this pressure degrades the lamp efficacy. To maintain the operating temperature for this pressure, the arc tube is normally enclosed in a vacuum flask or in an outer bulb at high vacuum.

The run-up time to full light output is 7 to 15 min (Figure 6-75). When first started, the light output is the characteristic red of the neon discharge, and this gradually gives way to the characteristic yellow as the sodium is vaporized. The hot re-ignition is good, and most low-pressure sodium lamps restart immediately after interruption of the power supply.

Efficacy. Low current density is vital to efficient generation of light. High densities result in excitation of atoms to higher energy levels and thus a loss of efficacy in converting electricity to light. Thermal insulation increases efficacies to above 180 lm/W for the 180-W U-type low-pressure sodium lamp, or approximately 150 lm/W including ballast losses. The thermal insulation consists of a light-transparent, IR-reflecting layer on the inside of the outer envelope. It is generally made of indium oxide; previously tin oxide and internal glass sleeves were used.

Construction. There are two types of low-pressure sodium lamps: the linear and the hairpin, or U tube. The linear lamp has a double-ended arc tube, similar to a fluorescent lamp, with preheat electrodes sealed into each end. Its arc tube, made of a special sodium-resistant glass, is sealed into an outer vacuum jacket with a medium bipin base at each end.

The hairpin type has the arc tube double back on itself, with its limbs very close together (Figure 6-76). Two versions are available, based on different approaches to maintaining even distribution of sodium in the arc tube throughout life. Excess metallic sodium condenses at the coolest part of the lamp, generally at the bend of the arc tube. If not controlled, very low sodium concentrations will produce a

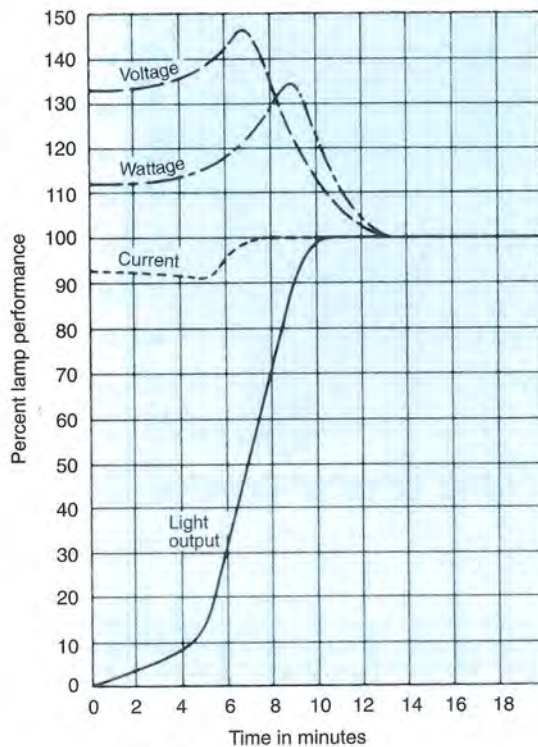


Figure 6-75. Low pressure sodium lamp performance during starting.

neon-argon arc in the tube. This is known as “operating bare.”

One hairpin design provides dimples in the outer surface of the arc tube; these serve as alternative cool points for the metallic sodium condensation. The dimples also inhibit migration of sodium due to vibration or gravitational effects. The alternative design uses a graded heat-reflecting film along the inside of the outer envelope, with the greatest amount of reflected heat at the bend.

Auxiliary Equipment. The low-pressure sodium arc, in common with all discharge lamps, has a negative volt-ampere characteristic. A current-limiting device, usually a transformer and reactor ballast, must be provided to prevent excessive lamp and line currents.

High-power-factor autotransformer ballasts are most commonly used. The required lamp starting voltages ranging between 400 and 550 V. A capacitor wired in parallel on the primary side increases the power factor to 90% or better. On this type of ballast, lamp regulation is excellent: lamp wattage and lumen output remain within 5% for a varying line voltage range of 20%. Constant-wattage ballast designs are also available.

Glow Lamps

These are low-wattage, long-life lamps designed primarily for use as indicator or pilot lamps, night lights, location markers, and circuit elements. They range from 0.06 to 3 W and have an efficacy of approximately 0.3 lm/W. A group of typical glow lamps is shown in Figure 6-77. These emit light having the spectral character of the gas with which they are filled. The most commonly used gas is neon, having a characteristic orange color. The glow is confined to the negative electrode. Glow lamps have a critical starting voltage, below which they are, in effect, an open circuit.

Like other discharge lamps, glow lamps require a current-limiting resistance in series. Glow lamps with screw bases have this resistor built into the base, while for unbased lamps or lamps with bayonet bases a resistor of the proper value must be employed external to the lamps.

Glow lamps filled with an argon mixture rather than neon radiate chiefly in the near UV region around 360 nm and are therefore used mainly to excite fluorescence in minerals and other materials as well as for some photographic applications.

Zirconium Concentrated Arc Lamps, Enclosed Type

These lamps use a direct-current arc constituting a concentrated point source of light of high luminance, up to 45 million cd/m². They are made with permanently fixed electrodes sealed into an argon-filled glass bulb. The light source is a small spot, 0.13 to 2.8 mm (0.005 to 0.11 in.) in diameter (depending on the lamp wattage), which forms on the end of a zirconium oxide-filled tantalum tube that serves as the cathode. The spectral power distribution is similar to that of a blackbody with a correlated color temperature of 3200 K. These lamps produce a candela distribution characterized



Figure 6-76. Construction of low pressure sodium lamps (U-tube or hairpin type).



Figure 6-77. Typical glow lamps with ANSI numbers (old trade numbers).

by the cosine law. They require special circuits that generate a high-voltage pulse for starting and a well-filtered and ballasted operating current. Suitable power supplies are recommended by the manufacturer. Figure 6-78 illustrates various examples of side- and end-emission lamps.

Pulsed Xenon Arc (PXA) Lamps

These are ac xenon lamps with two active electrodes (a polarized xenon lamp has current flowing in only one direction

and one active electrode). A switching reactor in series with the low-pressure lamp forces 50 to 100 peak amperes (120 pulses per second) through the lamp. The reactor also supplies a continuous current of 2 to 3 A to keep the lamp operating between pulses. The spectrum produced is characteristic of xenon, typically 6000 K. PXA lamps are available in linear and helical types.

The efficacy of these sources is approximately 35 to 40 lm/W. Available lamp wattages range from 300 to 8000 W, and forced-air cooling is required during operation.

PXA lamps are used in the graphic arts industry for applications requiring instant start; high-intensity, stable light output; and daylight-quality color temperature.

Flashtubes

These light sources are designed to produce high-intensity flashes of extremely short duration. They are primarily used for photography; viewing and timing of reciprocating and rotating machinery; airport approach lighting systems, including navigation aids, obstruction marking, and warning and emergency lights; laser pumping; and entertainment applications.

A conventional flashtube consists of a transparent tubular envelope of glass or fused silica (quartz) that has its main discharge electrodes internally located near the extremities and usually has an external electrode of wrapped wire for triggering. It generally contains very pure xenon gas at a pressure below atmospheric, usually in the range of 25 to 80 kPa (3.63 to 11.6 lb/in.²). Sometimes other gases such as argon, hydrogen, and krypton are added to the xenon to obtain

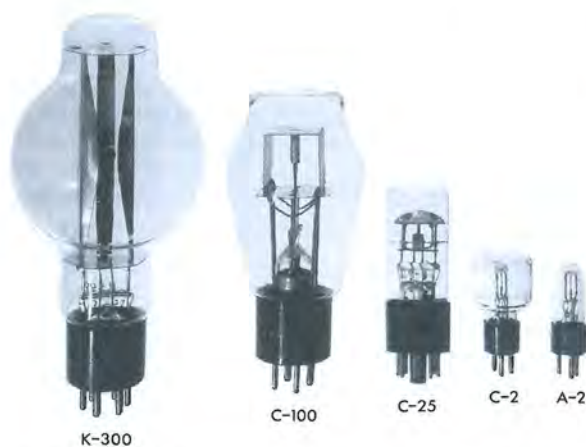


Figure 6-78. Side and end-emission concentrated arc lamps.

different spectral power distributions or different electrical, thermal, and deionization characteristics. With a voltage applied across its main electrodes, the tube acts as a high impedance or open circuit until a trigger pulse ionizes the gas within the tube. A trigger pulse induces ionization and thereby causes the xenon gas to become conductive. A discharge then occurs between the main electrodes, whereupon the gas becomes highly luminescent.

A xenon flashtube converts up to 35% of the input energy to light. The luminous efficacy ranges from 30 to 60 lm/W. The spectral quality is close to that of daylight, having a correlated color temperature of approximately 6000 K, so that the radiation encompasses the entire visible spectrum and extends into the UV and near IR (Figure 6-79). Flashtubes are available in many sizes and shapes to suit the user and the type of optical system employed. The most common types are straight (linear), wound (helix), and U shape. Other configurations are available for special applications. Figure 6-80 shows some typical commercially available flashtubes.

Energy and Life. For single-flash operation the limit to the amount of energy that can be consumed depends on the desired tube life measured in useful flashes. This life is affected by the rate of envelope wall blackening and destruction of the tube or its parts. Flashtubes designed for very high loading have envelopes made of fused silica, which can withstand high thermal shock. The peak power encountered during a discharge produces a thermal shock that could shatter the envelope; hence, to maximize the energy per flash the thermal shock must be limited. This can be done by reducing the peak current, which also lengthens the flash duration. To limit peak current and thermal shock as well as control the pulse duration, inductance is added in series within the discharge loop.

Normally, the life expectancy of a flashtube can be re-

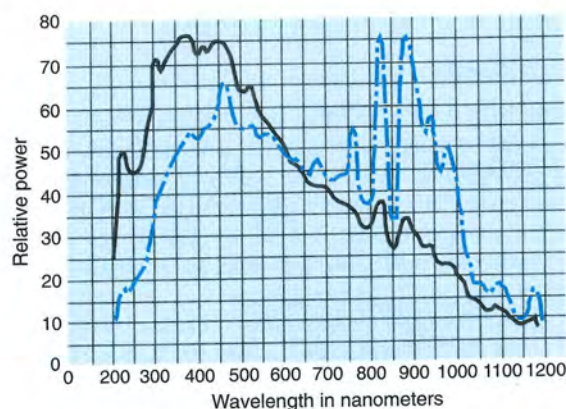


Figure 6-79. Spectral power distribution of a typical xenon-filled flashtube for two different discharge conditions: (a) high voltage, low capacitance (solid line), and (b) low voltage, high capacitance (dashed line).



Figure 6-80. Typical flashtubes.

lated to the percentage of explosion energy expended by a flash in a particular application. The explosion energy is defined by manufacturers as the energy level at a given flash duration that will cause the tube to fail within ten flashes, usually by disintegration of the envelope. The life can be approximated as follows:

Energy (% of explosion energy)	Flashtube Life (no. of flashes)
100	0-10
70	10-100
50	100-1000
40	1,000-10,000
30	10,000-100,000
20	100,000-1,000,000
5	>1,000,000

Limits of Power Input. The average power input is a product of the energy per flash and the flash rate. The maximum power that any flashtube can dissipate is determined by the envelope area, the type of envelope material, and the method of cooling, such as free air convection, forced air convection, or use of a liquid coolant. For fused silica envelopes the maximum input power can be approximated as follows: free air convection, 5 W/cm² (32.3 W/in.²); forced air convection, 40 W/cm² (258 W/in.²); liquid cooling, 200 W/cm² (1290 W/in.²).

Energy Storage Banks. The electrical energy that subsequently is discharged through the flashtube to produce light is stored in a capacitor bank. This bank must be capable of rapid discharge into a very low impedance load. Therefore, it must have a rather low inductance as well as a very low equivalent series resistance. It must also be capable of storing energy at a high voltage without significant leakage. Typical voltages vary from about 300 to 4000 V. Current banks use aluminum electrolytic, paper-oil or metalized paper capacitors designed specifically for energy storage applications. All are highly efficient in delivering energy to the flashtube. The type selected depends upon the voltage, temperature, and life, as well as size and weight limitations.

Electronic Circuitry. In addition to discharge circuitry, a conventional xenon flash system has a charging circuit and a trigger circuit (Figure 6-81). The charging circuit accepts primary electrical power at low voltage, transforms and rectifies it to higher voltage, and applies it to the capacitor bank, where it is stored as potential energy. The luminance of the flashtube depends upon its loading, which in turn depends on the capacitance of the energy storage capacitor and the voltage across it, in accordance with the formula:

$$\text{loading in joules} = CV^2$$

where

C = capacitance in μF ,

V = voltage across the tube (and capacitor) in kV.

The trigger circuit used for producing the high-voltage ionizing pulse consists of a low-energy capacitor discharge sys-

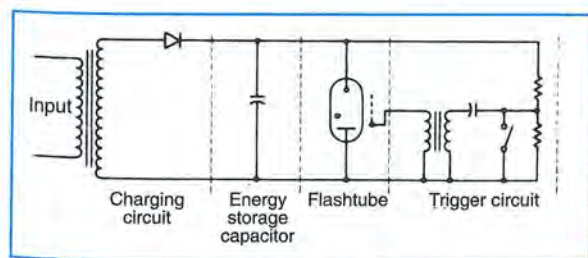


Figure 6-81. Basic elements of a typical flashtube power supply.

tem driving a pulse transformer. The pulse transformer establishes an electric field that starts the ionization process and causes the gas to conduct. This pulse usually is applied to the external trigger wire (external electrode), but in some applications it is applied across the main discharge electrodes by a pulse transformer with a very low secondary impedance in series with the flashtube discharge circuit.

By varying the voltage to the capacitor bank and hence its capacitance, and by the insertion of inductance in the discharge circuit, it is possible to vary both the light output and the flash duration of the system. The flash duration is dependent on the value of the capacitor, the inductance of the discharge circuit, and the effective impedance of the flashtube. Although the flashtube is a nonlinear circuit element, its effective impedance can be approximated according to the formula:

$$\text{flashtube impedance} = \rho L/A$$

where

ρ = plasma impedance in $\Omega \times \text{cm}$,

L = arc length in cm,

A = cross-sectional area of the arc in cm².

At current densities encountered in usual practice, ρ has a value of approximately 0.02 $\Omega\text{-cm}$.

Flashtubes with their associated circuitry can be designed to operate with flash energies from fractional watt-seconds to 20,000 watt-seconds, with durations from approximately one microsecond to many milliseconds, and with repetition rates from a single flash up to 1000 flashes per second. Even higher repetition rates can be attained with special circuitry and flashtube design.

Linear-Arc Lamps

Linear-arc quartz envelope lamps are available for both continuous wave and pulsed operation. Lamps operated in the pulsed mode are discussed above under flashtubes. Forced-air-cooled long-arc xenon lamps are made with arc lengths up to 1.2 m (4 ft), bore diameters up to 12 mm (0.47 in.), and wattages up to 6 kW. These lamps are used for special illumination requirements and solar simulation and have an efficacy of approximately 30 lm/W.

Water-cooled long-arc xenon and krypton lamps are made with arc lengths up to 0.3 m (1 ft.), bore diameters up to 10 mm (0.39 in.) and wattages up to 12 kW. Their main application is for laser pumping; krypton arc lamps are especially suitable for pumping neodymium-doped yttrium-aluminum garnet (Nd:YAG) lasers.

Forced-air-cooled mercury and halide-doped long-arc lamps are available in lengths up to 1.2 m (4 ft), bore diameters up to 10 mm (0.39 in.), and wattages up to 5 kW. They are used for UV photochemical applications, including the curing of paints, varnishes, and coatings.

Mercury capillary lamps are made with arc lengths up to 150 mm (6 in.), bore diameters from 0.08 in. (2 mm), and wattages up to 6 kW. They are used for UV photoexposure in the semiconductor and other industries. They are also finding use in the rapid thermal processing of silicon wafers.

All linear arc lamps use special ballasts and high-voltage starting devices. Manufacturers' recommendations for operation should be carefully followed.

ELECTROLUMINESCENT LAMPS⁸⁵⁻⁸⁸

An electroluminescent lamp is a thin (typically less than 1.2 mm [0.05 in.]), flat-area source in which light is produced by a phosphor excited by a pulsating electric field. These lamps are used in decorative lighting, instrument panels, switches, emergency lighting and signs, and for backlighting liquid crystal displays (LCDs).

An electroluminescent lamp is a plate capacitor with a phosphor embedded in its dielectric and with one or both of the electrode plates translucent or transparent (Figure 1-20). Green, blue, amber, yellow, or white light is produced by choice of phosphor. The green phosphor has the highest luminance. Lamps are available in rigid ceramic or flexible plastic and are easily fabricated into simple solid or complex multisegmented shapes in lengths as long as 1500 ft. The lamps have thin profiles, light weight, and generate little heat. Some can operate in exterior conditions from -40°C to 121°C (-40°F to 250°F).

The longevity of these lamps depends on isolating the plates and dielectric from humidity during manufacture and use. Their luminance varies with applied voltage, frequency, temperature, and time as well as with the type of phosphor and lamp construction. Electroluminescent lamps can be dimmed. The relationship between voltage and luminance for ceramic and plastic electroluminescent lamps is shown in Figure 6-82. Unlike that of some light sources, the color does not change as the voltage is increased or decreased. At 120 V, 60 Hz, the luminance of the ceramic form with the green phosphor is approximately 0.33 cd/ft^2 (3.5 cd/m^2); the luminance of the plastic form can be as high 2.5 cd/ft^2 (27 cd/m^2) under these conditions, or up to 11.6 cd/ft^2 (125 cd/m^2) at 120 V, 400 Hz. With the ceramic form at 600 V, 400 Hz, a luminance of 6.5 cd/ft^2 (70 cd/m^2) has been achieved.

Electroluminescent lamps have long life and low power requirements. They usually do not fail abruptly, and because of this, useful life is taken as the number of operating hours after which luminance falls below a specified level. Some electroluminescent lamps using long-life phosphor have operated continuously for more than ten years while powered at 115 V, 400 Hz. The number of operating hours after which the luminance falls to 50% of initial has been used for comparing lamp performance, but this can vary greatly depending on the drive voltage and frequency and the type of phosphor used (Figure 6-83). The value of the time to half

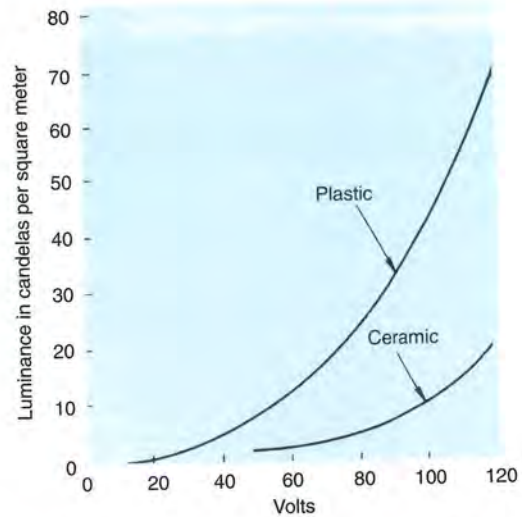


Figure 6-82. Luminances of green ceramic and plastic electroluminescent lamps operated at 400 Hz as a function of voltage.

luminance for flexible-type lamps operated at 115 V, 400 Hz can vary from 1000 to 30,000 h, depending on the type of phosphor. Typical initial current and power at these parameters are 1.2 mA and 40 mW/in.²

The types of electroluminescent devices explained above require high-voltage drivers, which could be a negative feature for use in certain applications. A new type of electroluminescent material known as light emitting polymer (LEP) that operates at low voltage was discovered in 1990. LEPs are organic semiconducting materials that exhibit light emit-

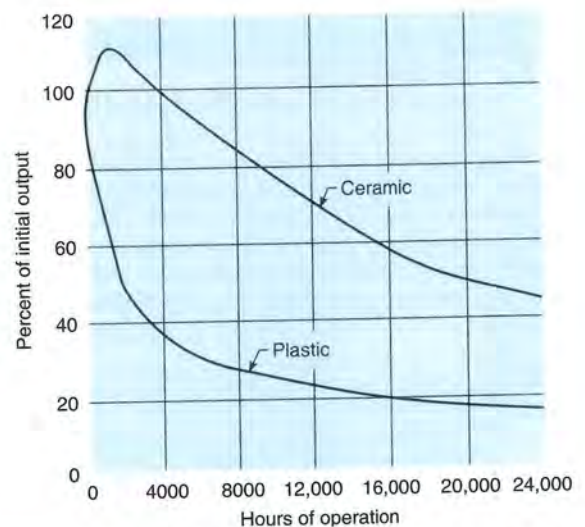


Figure 6-83. Light output versus hours of operation for green ceramic and plastic electroluminescent lamps.

ting characteristics similar to conventional inorganic semiconductors such as light emitting diodes (LEDs) (see section below). In addition, they possess the desirable processing and mechanical characteristics of plastics. A key feature of LEP is that it emits light in a way that is similar to conventional LEDs; in addition, the emitted light can be patterned like LCDs. Therefore, this technology lends itself to the creation of ultrathin lighting displays that operate at low voltage. LEP technology is still in its infancy. Monochromatic devices that are suitable for small display lighting, such as digital readouts on electronic devices, are beginning to emerge commercially.

LIGHT-EMITTING DIODES

AlInGaP and InGaN Light-Emitting Diodes⁸⁹⁻⁹⁶

Aluminum indium gallium phosphide (AlInGaP) and indium gallium nitride (InGaN) are the two most common light emitting diode (LED) technologies, displacing older gallium arsenide phosphide (GaAsP), gallium phosphide (GaP), and aluminum gallium arsenide (AlGaAs) LEDs. The following is an overview of these technologies from the perspective of illuminating engineering. Additional information is available for AlInGaP LEDs (References 89–92) and InGaN LEDs (References 93–94), and for LEDs in general (References 95–96). Details on the physics of LEDs is available in Chapter 1, Light and Optics.

Intensity and Color

Manufacturers commonly test and bin each LED for luminous intensity and color. Like incandescent reflector lamps, the luminous intensity of LED devices is specified in terms of its beam angle. However, LED manufacturers refer to this as the viewing cone angle or the $2\theta_v$ angle (in degrees). Typically, all LEDs within a bin do not vary in luminous intensity by more than a factor of two. Because of the difficulty in measuring luminous intensity accurately, there is an expected 10% overlap between adjacent bins.

The color of an LED device is specified in terms of the dominant wavelength emitted, λ_d (in nanometers). Amber AlInGaP and InGaN blue and blue-green LEDs are binned by dominant wavelength, λ_d . Mixing two color bins in the same pixel matrix can produce an uneven color appearance and is not recommended. Dominant wavelengths for the colors produced by AlInGaP and InGaN LED devices are plotted on the 1931 CIE chromaticity diagram, shown in Figure 6-84. AlInGaP LEDs produce the colors red (626 to 630 nm), red-orange (615 to 621 nm), orange (605 nm), and amber (590 to 592 nm). InGaN LEDs produce the colors green (525 nm), blue green (498 to 505 nm), and blue (470 nm).

Typical spectral half-bandwidths are usually specified on LED lamp data sheets as $\Delta\lambda_{1/2}$. For AlInGaP LEDs, the typical half-bandwidth is approximately 17 nm, and for InGaN LEDs it is approximately 35 nm.

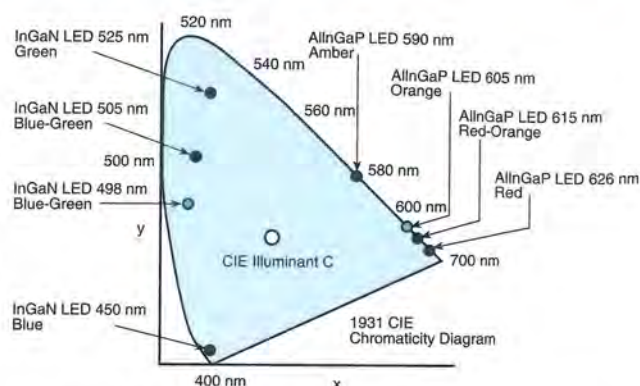


Figure 6-84. Dominant wavelengths, λ_d (nm), plotted on the 1931 CIE Chromaticity Diagram.

The luminous intensity, color, and forward voltage of AlInGaP LEDs are affected by the temperature of the LED p-n junction. As the temperature of the LED p-n junction increases, the luminous intensity decreases, the dominant wavelength shifts towards longer wavelengths, and the forward voltage drops. The variation in luminous intensity of InGaN LEDs with operating ambient temperature is small (about 10%) from -20°C to 80°C . The small variations are not readily visible and need not be taken into account for most applications. The dominant wavelength of InGaN LEDs does vary with LED drive current; as the LED drive current increases, dominant wavelength moves toward shorter wavelengths.

Dimming

LEDs may be dimmed to 10% of maximum by reducing the drive current and still have even luminous intensity across an LED matrix. Pulse width modulation (PWM) is the preferred method for dimming LEDs. LEDs may be dimmed to 0.05% of maximum by using PWM. With PWM, the peak pulse current and the pulse rate remains constant while the duration of the on-time pulse is shortened.

Reliability

The rated maximum junction temperature (T_{JMAX}) is the most critical parameter on an LED device data sheet. Temperatures exceeding this value usually result in catastrophic failure of a plastic encapsulated LED device. T_{JMAX} is actually a limitation related to packaging rather than to the LED chip.

Lamp life for LED devices is based on the mean time between failures (MTBF). MTBF is determined by operating a quantity of LED devices at rated current in an ambient temperature of 55°C and recording when half the devices fail.

Lumen depreciation for AlInGaP LED devices is shown in Figure 6-85. The dotted line is an extrapolation from currently available data. The same information for InGaN LED

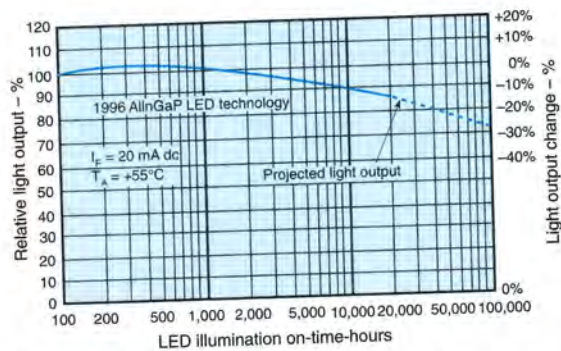


Figure 6-85. Projected long-term light output degradation for AlInGaP LED technology at 55°C.

devices is shown in Figure 6-86. Fewer data are available for this technology, and those data were collected at 25°C (77°F). The dotted line is extended for currently available data.

AlInGaP and InGaN LED Package Configurations

Amber, orange, and red AlInGaP plastic T-1 $\frac{3}{4}$ LED lamps (Figure 6-87a) with circular radiation patterns have been the preferred package for high-luminance applications such as traffic signals, variable message signs, commercial advertising signs, and EXIT signs. InGaN blue-green plastic T-1 $\frac{3}{4}$ LED lamps are used in green traffic signals. InGaN blue and green and AlInGaP amber and red plastic T-1 $\frac{3}{4}$ oval LED lamps with elliptical radiation patterns are used in color graphical commercial LED advertising signs and large scale outdoor full color video displays. Higher intensity AlInGaP amber and red LEDs (Figure 6-87b) were designed primarily for automotive exterior lighting, such as tail lights and turn signals. Now other high-luminance designs are incorporating these LED devices. New plastic package configurations (Figure 6-87c) incorporating both AlInGaP and InGaN LED devices, have been designed to illuminate large areas.

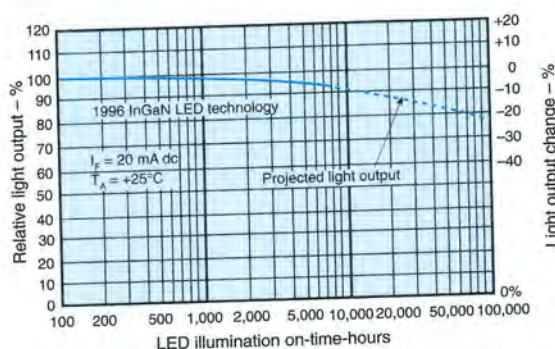


Figure 6-86. Projected long-term light output degradation for InGaN LED technology at 25°C.

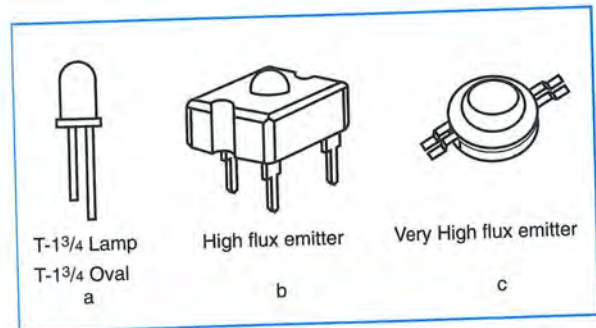


Figure 6-87. Plastic package high-performance LED devices.

AlInGaP amber and red plastic LED surface mount (SMT) emitters (Figure 6-88a and b) are popular on PC board assemblies. The brightness of chip LED devices is low and useful only for applications where the ambient light level is also low. The subminiature LED devices provide higher brightness and can be used in more applications.

White LED Devices

Efforts have been undertaken to develop LED devices that produce white light. One method is to combine red, green, and blue LED chips in the same package to produce white light. However, individuals with color deficiencies may not see the emitted light as white.

Recently InGaN LED devices have been combined with photoluminescent phosphors (see Chapter 1, Light and Optics, for information on photoluminescence). The short-wavelength energy from the InGaN LED device induces fluorescence in the phosphor that is encapsulated in the epoxy surrounding the LED chip. The photoluminescent phosphor emits a broad spectral distribution, which in combination with the spectrum of a blue LED, produces a blue-white color (Figure 6-89). Color deficient individuals will still see the combined spectral distribution as blue-white light.

Photometric and Electrical Characteristics of LEDs

Because they are highly directional light sources, LEDs often are specified in terms of their peak intensity, in millicand-

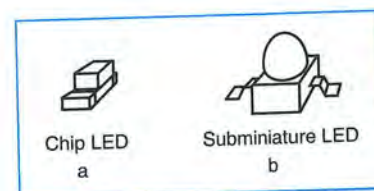


Figure 6-88. Plastic package surface-mount (SMT) LED devices.

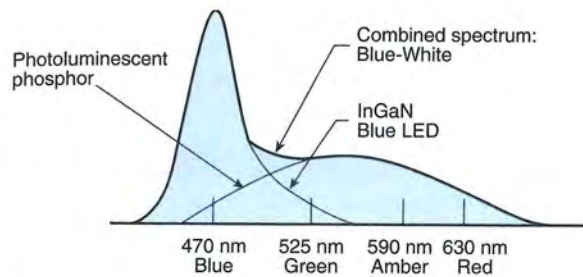


Figure 6-89. Spectral distribution of a blue-white LED/photo-luminescent phosphor device.

dēlas (mcd). Depending on their viewing cone angle, peak intensities of high-output AlInGaP LEDs range from 100 to 650 mcd for red lamps, and from 120 to 1100 mcd for amber ones. Blue InGaN LEDs with narrow viewing cone angles can have peak intensities greater than 500 mcd.

Typical operating voltages for LEDs can range from 1.5 to 4 V. With a typical current of 20 mA, the input power of a single LED can range from approximately 0.03 to 0.08 W. A single red traffic signal head might contain from 20 to 200 individual LED components and have an input power of 10 to 15 W.

Luminous efficacy of LEDs is defined as the emitted luminous flux (in lm) divided by the emitted radiant power (in W). This is commonly called internal efficacy. Using this definition, blue LEDs can have a rated internal efficacy in the order of 75 lm/W; red LEDs, approximately 155 lm/W; and amber ones, 500 lm/W. Taking into consideration losses due to internal re-absorption, the luminous efficacy is on the or-

der of 20 to 25 lm/W for amber and green LEDs. This definition of efficacy is called external efficacy and is analogous to the definition of efficacy typically used for other light source types. See Chapter 1, *Light and Optics*, for definitions of these terms most relevant to illuminating engineering.

LASERS

The word “laser” is an acronym for “light amplification by stimulated emission of radiation.” Invented in 1960, a laser is a device that concentrates light waves on an intense, low-divergence beam. Even though the light source is an inefficient converter of electrical energy to light energy, a single laser becomes incredibly efficient when applied to a very large-scale lighting requirement (Figure 6-90).

What is collectively referred to as a laser is really a complete lighting system comprised of three main parts: the laser tube, a gas-filled tube that emits the light; the projector that manipulates or scans the beam; and the computer hardware and software that stores and controls the performance. Chapter 1, *Light and Optics*, gives details on laser physics.

Lasers are used in hundreds of different applications ranging from corporate theater and major concert tours to surveying and construction. Industrial business theater presentations use sophisticated laser graphics and animation to augment multi-image slide and video productions. Laser effects highlight or emphasize a corporate message or speaker with dramatic flair. Many large corporations use lasers at their conventions and special events. Performers have incorporated lasers in their performances and music videos. Large-scale uses have included theme parks.

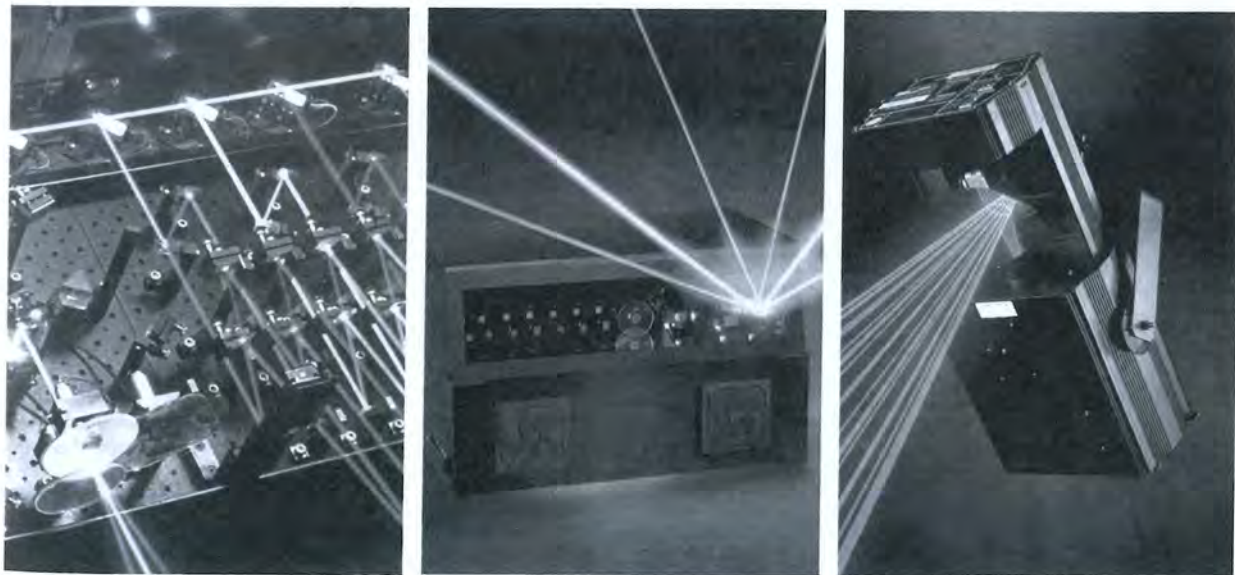


Figure 6-90. Laser display equipment (left, optical components; center, laser head; right, display unit mounted for remote control).

The laser tube filled with either argon or krypton gas emits the visible light to be manipulated into spectacular light sculptures and paintings. Argon lasers emit light in the blue-green range. For aerial projections to be visible, all the light energy from large-frame 20-watt lasers must be used. For projected images, however, the argon beam can be divided into its component wavelengths of blue and green to create beam colors that can be manipulated separately. Krypton lasers emit red light, which provides important color contrast and spectrum expansion for facade projections.

Laser installations and performances are regulated by federal, state, and local regulations designed to protect public health and safety. The concentrated energy in the low-divergence beam (within a determinable distance from the beam origin) could cause retinal damage if projected directly into the eye. Consequently, various regulations call for minimum separation distances (e.g., 3-meter vertical, 2.5-meter lateral) between beam projections and humans.

NUCLEAR LIGHT SOURCES

Nuclear light sources are self-contained and require no power supply. They typically provide illumination for instrument panels, controls, clocks, and exit signs (see Chapter 29, Emergency, Safety, and Security Lighting).

These sources consist of a sealed glass tube or bulb internally coated with a phosphor and filled with tritium gas. Low-energy beta particles (electrons) from the tritium, an isotope of hydrogen, strike the phosphor, which in turn emits light of a color characteristic of the type of phosphor used. Thus, the mechanism of light production is very similar to that in a conventional television tube. The higher the ratio of the quantity of tritium to the phosphor area, the greater the luminance. The luminance can range up to 7 cd/m² (0.65 cd/ft²), with a typical average of 1.7 cd/m² (0.16 cd/ft²) (this level is approximately that of an illuminated car instrument panel), and the sources can be supplied in a variety of colors. Highest luminances are obtained in the green and yellow phosphors, and green is the usual color supplied. Since tritium has a half-life of 12.3 yr, one might expect the brightness of the source to decay likewise. In reality, the half luminance typically is reached in 6 to 7 yr, and the useful life of these lamps is currently about 15 yr. These light sources can be supplied in very small sizes, down to 5 mm (0.2 in.) in diameter by 2 mm (0.079 in.) in length.

The glass wall is impervious to tritium and completely absorbs any beta radiation not already absorbed by the phosphor. The unit is thus a completely sealed source and does not present any radiation hazard. Glass capsules can be produced in a wide variety of shapes and sizes and are usually made to normal glassworking tolerances. All applications of these lamps are monitored by the Nuclear Regulatory Commission in the United States and by Atomic Energy Canada in Canada.

CARBON ARC LAMPS

Carbon arc lamps were the first commercially practical electric light sources. They were used for many years in applications where extremely high luminance, high correlated color temperature, and/or high color rendering were necessary, such as in motion picture projection lamphouses and for theatrical followspots, searchlights, and film production daylight supplemental lighting. In most of those applications, xenon short arc and metal halide light sources have replaced carbon arc.

Carbon arcs are operated in lamphouses that shield the outside from stray radiation. These lamphouses incorporate optical components such as lenses, reflectors, and filters for eliminating undesired parts of the spectrum.

For more information about different types of carbon arc lamps, their operating characteristics, and power sources, see previous editions of the IESNA *Lighting Handbook*.

GASLIGHTS

Gaslights use gaseous fuels for light and decorative purposes. They use open gas flames or incandescent mantles of the upright and inverted types. For more information, see previous editions of the IESNA *Lighting Handbook*.

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Luminaires

A luminaire is a device to produce, control, and distribute light. It is a complete lighting unit consisting of the following components: one or more lamps, optical devices designed to distribute the light, sockets to position and protect the lamps and to connect the lamps to a supply of electric power, and the mechanical components required to support or attach the luminaire.

This chapter provides information for both specifiers and manufacturers of luminaires. It describes most common types of luminaires, how they are used, and how their performance is evaluated, and gives a general classification system useful for understanding their application. With the exception of lamps (light sources), the characteristics, design, and manufacture of luminaire components are described. Detailed information for the specific applications of luminaires can be found in the appropriate application chapters.

GENERAL DESCRIPTION

Light Sources

Luminaires are designed and manufactured for all common types of electric lamps. Luminaires are commonly available for these lamps:

- Incandescent filament including tungsten halogen and infrared (heating) lamps
- Fluorescent
- Compact fluorescent
- Induction or electrodeless lamps, including fluorescent and sulfur lamps
- High-intensity discharge lamps, including metal halide, high-pressure sodium, and mercury
- Low-pressure sodium lamps

Luminaires are less common for xenon arc and carbon arc lamps.

The size, materials, thermal properties, photometric performance, and power requirements of a luminaire depend on the type of lamp used. For example, lamps that produce a large amount of infrared (IR) radiation (heat) require luminaires that are vented for convection, and fluorescent lamps that are sensitive to environmental temperature must be protected from low air temperatures.

Light Control Components

The lamps used in some luminaires have integrated light control components. These are usually incandescent and tungsten-halogen lamps with a reflective coating and/or refracting prisms on the bulb. These integral lamp components produce useful beams and patterns of light without any auxiliary optical control. In these cases, most of the light control is provided by the lamp; the luminaire is simply an appliance to hold the lamp, deliver electric power, and perhaps permit the lamp to be aimed in different directions.

Most lamps emit light in virtually all directions, and their efficient application requires light control components to collect and distribute the light. Four types of light control components are commonly used: reflectors, refractors, diffusers, and louvers or shields. See the sections “Optical Control” in Chapter 1, Light and Optics, and “Materials Used in Luminaires” in this chapter for detailed discussion of optical control by reflection and refraction.

Reflectors. A reflector is a device, usually of coated metal or plastic, that has a high reflectance and is shaped to redirect by reflection the light emitted by the lamp. The surface finish of luminaire reflectors usually is classified as specular, semi-specular, spread, or diffuse. For more information, see “Optical Control” in Chapter 1, Lighting and Optics.

Some applications require the reflector to control the light very precisely, so specular or semi-specular reflecting material is used. Metal reflectors are formed and then polished or chemically coated to produce a specular finish. In some cases, metal reflectors are manufactured from metal stock that has already been treated to produce a specular finish. Plastic reflectors are molded and then coated with aluminum by vaporization. Examples of specular reflectors are those used to control the light from a metal halide lamp to produce a narrow beam of light for sports lighting, and the parabolic louvers in fluorescent lamp troffers.

In some luminaires the reflector does not have to control the light very precisely, and it is sufficient for the reflector to have a high but nondirectional reflectance. An example of this is the white, slightly specular, coated metal reflectors in some large fluorescent lamp luminaires. On the other hand, diffuse reflectors have very little effect on the distribution of light and are uncommon in luminaires. Other applications and lamps require reflectors with special surface finishes, such as semi-specular or peened materials, or coatings to reduce color separation upon reflection (iridescence) when us-

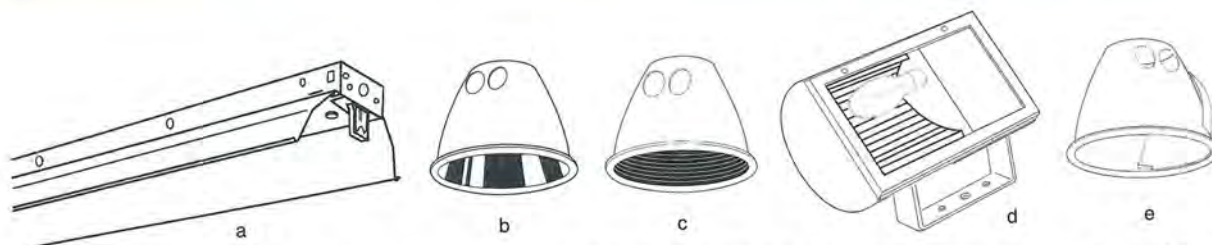


Figure 7-1. Examples of reflectors: (a) linear faceted, coated steel reflector in a strip fluorescent lamp luminaire, (b) and (c) spun specular and grooved aluminum reflectors for a compact fluorescent downlight luminaire, (d) faceted reflector for a floodlight luminaire, and (e) reflector with "kicker" to direct light for wall-wash luminaire.

ing certain fluorescent lamps. Examples of reflectors are shown in Figure 7-1.

In some cases, reflectors have properties varying with wavelength. Alternating layers of materials with differing indices of refraction are applied to glass. These layers have a thickness approximately that of the wavelength of light (500 nm). Interference effects produce reflection that changes with wavelength. This is useful if it is desirable to reflect light but not reflect long-wavelength thermal radiation or, conversely, to reflect the long wavelength radiation and pass light. These reflectors are used when it is necessary to direct light and control the heat generated by the lamps.

Refractors. Refractors are light control devices that take advantage of the change in direction that light undergoes as it passes through the boundary of materials of differing optical density (index of refraction), such as air to glass or air to plastic (see Figure 7-2). A material, usually glass or plastic, is shaped so that light is redirected as it passes through it. This redirecting can be accomplished with linear (extruded,

two-dimensional) prisms or with three-dimensional pyramidal-shaped prisms. These prisms can be either raised from the surface of the material or embossed into it. They are usually small enough to become a type of surface treatment on one side of an otherwise flat sheet of glass or plastic. The entire sheet is referred to as a prismatic lens.

A collection of small prisms, acting in concert, can be used to control the directions from which light leaves a luminaire. This redirection can be used to partially destroy images and therefore to obscure lamps and reduce luminance by increasing the area over which the light leaves the luminaire. In some cases the sheet containing prisms is shaped to provide additional control. In specialized applications, such as the refractors used for some street lighting luminaires, the prisms are on both surfaces of the material.

Another application of refracting material takes advantage of total internal reflection. In this case the refracting material is shaped so that light passes into it through its first surface and mostly is reflected from the second surface back

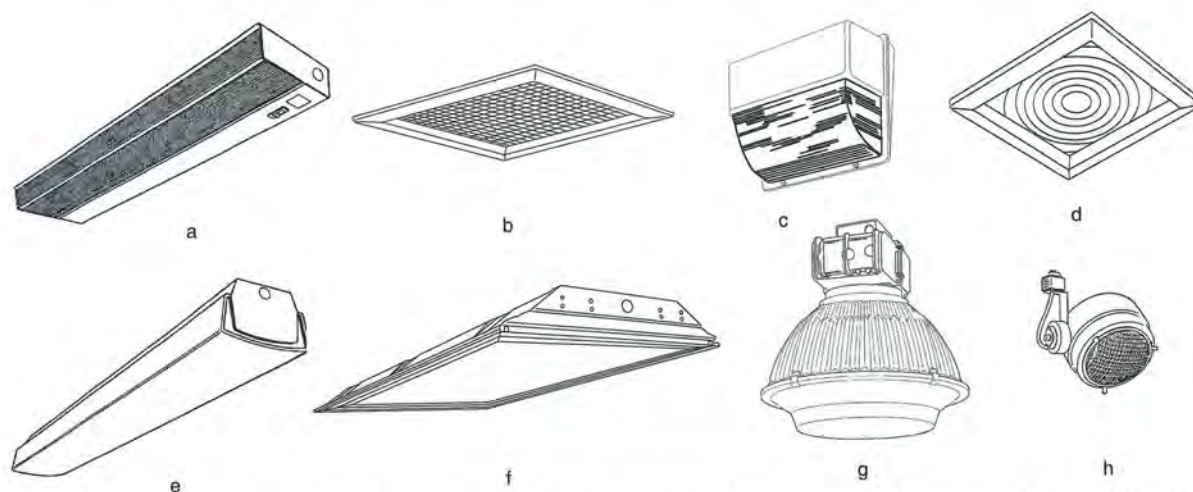


Figure 7-2. Examples of refractors: (a) prismatic lens on surface-mounted fluorescent lamp luminaire, (b) recessed luminaire with spread lens, (c) glass refractor on an outdoor area luminaire, (d) Fresnel refractor, (e) wraparound prismatic lens on a fluorescent lamp luminaire, (f) prismatic lens on recessed fluorescent lamp luminaire, (g) low-bay industrial luminaire with prismatic refractor, and (h) track luminaire with spread lens refractor.

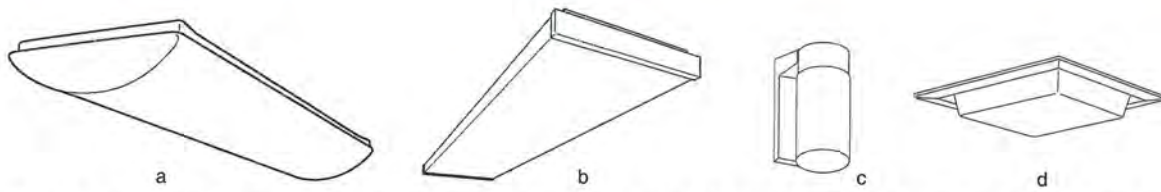


Figure 7-3. Examples of diffusers: (a) and (b) wrap-around white diffusers for fluorescent lamp luminaires, (c) jelly jar diffuser for compact fluorescent lamp luminaire, and (d) drop glass diffuser for metal halide lamp luminaire.

into the material and out the first surface. Some glass and plastic industrial luminaires use this type of light control. This is also the basis for the operation of light pipes and fiber-optic luminaires.

For some luminaires, the lamp and application require a transparent cover to block ultraviolet (UV) radiation or prevent broken lamp components from falling out of the luminaire. Though providing little optical control, these cover plates often are referred to as lenses.

Diffusers. Diffusers are light control elements that scatter (redirect) incident light in many directions. This scattering can take place in the material, such as in bulk diffusers like white plastic, or on the surface as in etched or sandblasted glass. Diffusers are used to spread light and, since scattering destroys optical images, obscure the interior of luminaires, suppress lamp images, and reduce high luminances by increasing the area over which light leaves a luminaire. Examples of diffusers are shown in Figure 7-3.

Shades, Shields, Louvers, and Baffles. Shades and shields are opaque or translucent materials shaped to reduce or eliminate the direct view of the lamp from outside the luminaire (Figure 7-4). Shades are usually translucent and are

designed to diffuse the light from the lamp and provide some directional control.

Blades, usually opaque and highly reflective, can be shaped and positioned to eliminate the direct view of the lamp from certain directions outside the luminaire and to control the direction from which the light leaves.

If arranged in a rectangular grid, producing cells, they are called louvers. If arranged linearly they are called baffles. In large fluorescent lamp luminaires, louvers are designed so that the lamps are directly above the center of the cells formed by the louvers. In long narrow fluorescent lamp luminaires, baffles extend across the axis of the lamps.

Louvers and baffles often are made of specularly reflecting metal, though some are of coated plastic. Though intended to eliminate the direct view of the lamp at some angles, specular louvers and baffles can provide lamp images at other viewing angles by reflection. In turn, these images may produce images in the screen of computer VDTs. See Figure 7-4 for examples of baffles and louvers.

Fiber-Optic Luminaires. A fiber-optic illumination system is a distributed lighting system allowing remote source illumination of areas and objects. A fiber-optic lighting system

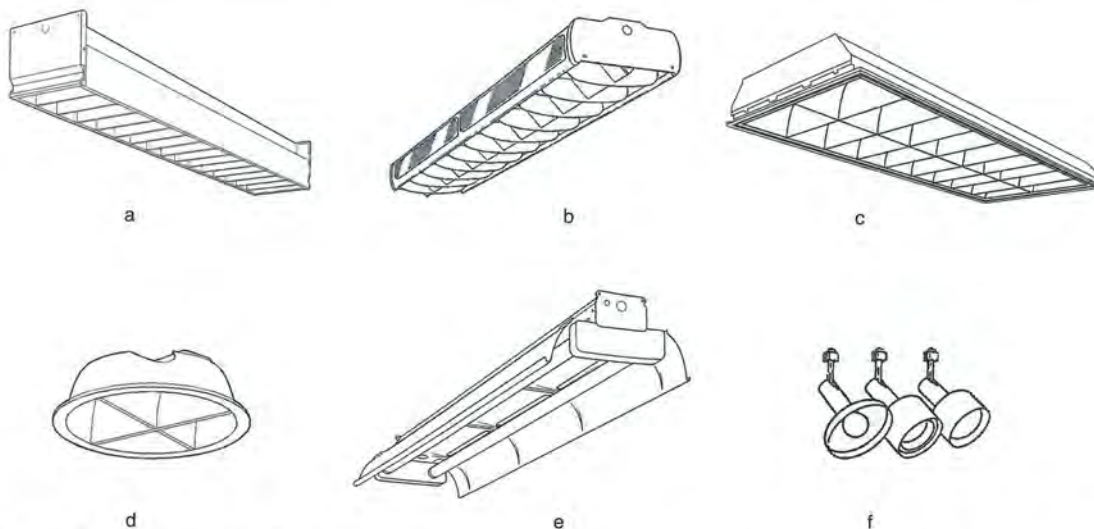


Figure 7-4. Examples of baffles, louvers, and shields: (a), (b), and (c) louvers for fluorescent lamp luminaires; (d) cross baffles for compact fluorescent lamp luminaires; (e) shield for industrial fluorescent lamp luminaire; and (f) hoods and cowls for track luminaires.

has a light source or illuminator, optical fiber, and various output fixtures selected to illuminate specific areas or objects. These systems can be used in lighting applications requiring the light source and light output to be separated, as in hazardous environments, wet locations, or in temperature-sensitive spaces. They also can be used when it is desirable to have sizes, shapes, or light output characteristics different from conventional luminaires.

Virtually all of the IR and most of the UV radiation from lamps, as well as the electrical connections needed to power the system, are absent from the illuminated space. The separation of source from output allows the use of various components within the source enclosure that can provide interesting optical effects at the output. Such components can include color or effects wheels and filters.

Illuminator. The illuminator is an assembly that houses the light source and positions the optical fibers within an output port, or ports, with respect to the source. It may include other components such as a cooling fan, various optical elements, filters, and color wheels or effects devices.

Since lamps are not point sources, the light is collected with a combination of reflecting and/or refracting optics. The collection efficiency is a function of both the size and shape of the light source (e.g., arc or filament) and the chemical as well as the physical characteristics of the fiber(s) receiving the light. Proper use of conventional nonimaging optical design methods enable the collection of 10 to 40% of the light into light guides.

The most commonly used lamps in optical fiber systems are tungsten-halogen and metal halide. Illuminators that incorporate halogen sources almost always includes a cooling fan. Applications that require greater light output and longer lamp life use metal halide high lamps. Other light sources (xenon, xenon metal halide, and sulfur lamps) occasionally are used in optical fiber illumination systems. These lamps have advantages that make them appropriate for certain specialized applications.

The illuminator often contains various accessories that affect the output. These include permanent filters such as IR, UV, or dichroic; rotating wheels that provide a variety of colors; and mechanical dimming or twinkling. Many tungsten-halogen illuminators are available with electronic dimming.

Optical Fiber. The principal function of optical fiber is to deliver light from the illuminator to the exit port. A fiber consists of at least two and often three concentric regions. These regions are the core, which is the light transmission medium; the cladding, which confines the light to the core, and the sheathing, which is an outer coating protecting the fiber from handling or interaction with the environment. In side lighting applications, the fiber is designed so that light is emitted uniformly from the sides. For end lighting applications, light propagates down the fiber by totally internally reflecting at the core-cladding interface. Since this reflectance is very nearly 1.0, light loss through the fiber is due almost solely to absorption and scattering. The absorp-

tion and scattering characteristics of the fiber material determine the attenuation. Total internal reflection requires a high incidence angle to the core-cladding interface, and this requires that light enter the fiber end within a certain acceptance angle. The acceptance angle is a function of the indices of refraction of the core and cladding. In general, the acceptance angle also defines the angle with which the light exits an optical fiber.

Output Optics. The nature of the optics placed on the output end of the fibers depends on the details of the application. The angular distribution of the light depends on the spread of the system's input illumination, and is typically between 60° and 80°. A wide array of fixtures that house shaped plastic or glass diffusers and/or lenses with different distribution characteristics is available to achieve many effects. In addition, numerous decorative fiber end fittings are available to create interesting display and decorative effects.

Optical fiber output fixtures typically are smaller and more lightweight than conventional luminaires because the fibers approach the characteristics of a directional point source and heat is of no concern. This allows many fixtures to be composed of plastic.

Mechanical Components

The mechanical components of a luminaire consist of a housing or general structure to support other components of the luminaire, and a mounting mechanism for the attachment of the luminaire to its support (Figure 7-5). In some luminaires the reflector is a separate component that is attached to the housing, as in a compact fluorescent lamp downlight. In other luminaires, the housing serves as the reflector, as in a fluorescent lamp troffer.

If the luminaire uses a refractor or transparent cover, then hinged frames or doors often are provided to hold the lens. Access for cleaning and relamping is through this door.

In damp or wet applications it is necessary to provide adequate seals to prevent migration of water into the luminaire. In some hazardous locations the housing and seals must keep explosive or flammable vapors from contact with high lamp surface temperatures or electric spark. These luminaires are said to be explosion proof.

Many recessed luminaires are vented to dissipate heat that can degrade lamp performance. In some applications, the luminaire is used as part of the building's heating, ventilating, and air conditioning system. Air is supplied to or removed from the room using the luminaire. In this case, airways are provided within the luminaire as well as attachments for air ducts and slots through which air enters or leaves the room.

Electrical Components

The electrical components of the luminaire operate the lamp (Figure 7-6). One or more sockets provide mechanical support for the lamp and furnish necessary electrical connec-

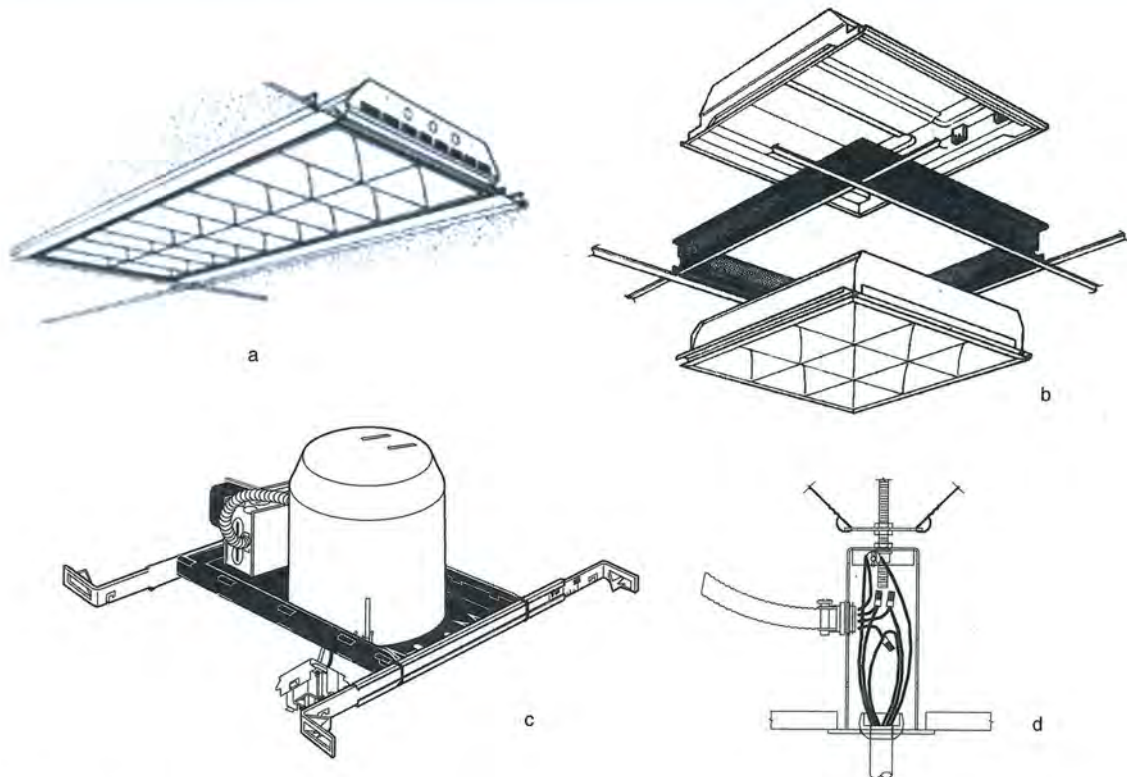


Figure 7-5. Examples of mechanical components of luminaires: (a) and (b) fluorescent lamp troffers showing housing and mounting to inverted-T ceiling system; (c) compact fluorescent lamp downlight showing housing, mounting for ballast, and mounting brackets; and (d) mounting and electrical connection for a pendant-mounted luminaire.

tions. For some lamps, usually single-ended, mechanical support is required in addition to the socket.

If required, the luminaire contains and supports ballasts, starters, igniters, capacitors, or emergency lighting devices. The size and power handled by these components often determine the size of the luminaire and the requirements for proper thermal performance. In a few applications, these components are too heavy, too loud, or too large to be in the luminaire. In these cases, the ballast and other auxiliary equipment are mounted remotely from the luminaire and lamp. The luminaire also contains wiring and connectors to connect the lamp socket and, if present, the ballast to the external wiring that brings electrical power to the luminaire.

Figures 7-7 through 7-12 show cross sections of typical luminaires with most of the major components shown. Even apparently simple luminaires contain many components.

LUMINAIRE TYPES AND CLASSIFICATION

Purpose of Classification

Luminaire classification helps specifiers and manufacturers describe, organize, catalog, and retrieve luminaire informa-

tion. The nature of luminaire classification has changed with the advance of computer and information technology. Modern lighting design and specification practice relies on computer-based luminaire databases, accessed on CD-ROM or over the Internet. This technology allows luminaire data to be updated frequently and easily. In such systems, a luminaire can be known by all of its characteristics, with any one being the path by which a search finds the luminaire in a database.

Methods for Classification

Luminaires can be classified according to source, mounting, construction, application, and/or photometric characteristics. Classifications by application and photometric characteristics are discussed in the next two sections.

Classification by Application. A common form of classification organizes luminaires by application. Many luminaire characteristics are determined by application, so this distinction proves useful in organizing luminaire information. Three application areas are usually distinguished: residential, commercial, and industrial. Within each application, luminaires can be classified by source, mounting, and con-

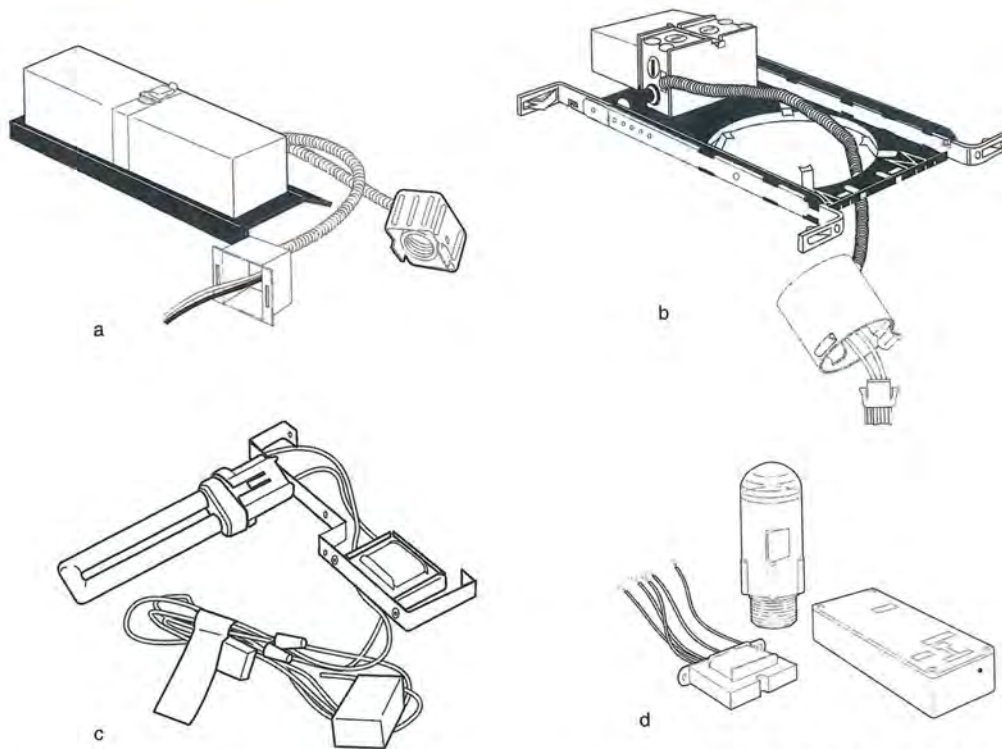


Figure 7-6. Electrical components, showing junction box, ballast, and lamp socket for (a) metal halide and (b) compact fluorescent lamp luminaires; (c) compact fluorescent lamp, socket, magnetic ballast, and connectors; and (d) photocell, transformer, and ballast for controlling outdoor luminaires.

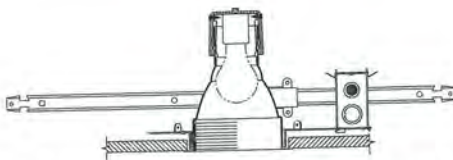


Figure 7-7. Incandescent lamp downlight showing housing, mounting, reflector, wiring, socket, and lamp.

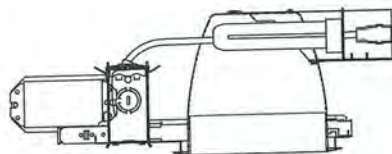


Figure 7-8. Compact fluorescent lamp downlight showing housing, mounting, reflector, wiring, socket, and lamp.

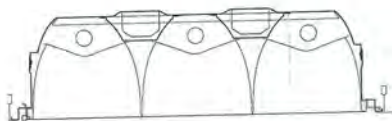


Figure 7-9. Fluorescent lamp troffer showing housing, mounting, reflector, lamps, and ballast.



Figure 7-10. Suspended fluorescent lamp luminaire showing extruded aluminum housing, reflector, lamps, and ballast.

struction. Examples of these include residential ceiling-mounted room luminaires using incandescent lamps, recessed fluorescent lamp troffer luminaires, and high bay suspended metal halide lamp luminaires.

Classification by Photometric Characteristics. Another form of classification uses the luminous intensity or flux distribution of the luminaire. For luminaires used indoors, a method specified by the International Commission on Illumination (CIE) is commonly used. For luminaires used outdoors, the NEMA and IESNA methods are used.

The CIE Classification System. The International Commission on Illumination provides a classification system based on the proportion of upward and downward directed light output. This system is usually applied to indoor luminaires.

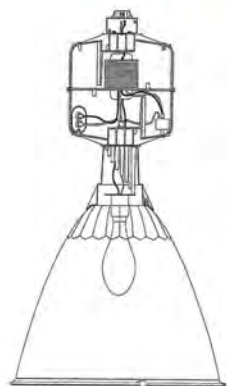


Figure 7-11. High-bay HID lamp luminaire showing housing, reflector, lamp, socket, magnetic ballast and capacitor, and mounting.

- **Direct lighting.** When luminaires direct 90 to 100% of their output downward, they form a direct lighting system. The distribution may vary from widespread to highly concentrated, depending on the reflector material, finish, and contour and on the shielding or optical control media employed.
- **Semidirect lighting.** The distribution from semidirect units is predominantly downward (60 to 90%) but with a small upward component to illuminate the ceiling and upper walls.
- **General diffuse lighting.** When the downward and upward components of light from luminaires are about equal (each 40 to 60% of total luminaire output), the system is classified as general diffuse. Direct-indirect is a special (non-CIE) category within this classification, in which the luminaires emit very little light at angles near the horizontal.
- **Semi-indirect lighting.** Lighting systems that emit 60 to 90% of their output upward are classified as semi-indirect.
- **Indirect lighting.** Lighting systems classified as indirect are those that direct 90 to 100% of the light upward to the ceiling and upper side walls.

Indoor Luminaire Classifications By Cutoff. There are several characteristics of indoor luminaire intensity distributions that are important for classification. This information can appear in the photometric report for a luminaire. See the section "Luminaire Photometric Report" later in this chapter.

- **Physical cutoff.** The angle measured from nadir at which the lamp is fully occluded.
- **Optical cutoff.** The angle measured from nadir at which the reflection of the lamp in the reflector is fully occluded.
- **Shielding angle.** The angle measured from the horizontal at which the lamp is just visible.

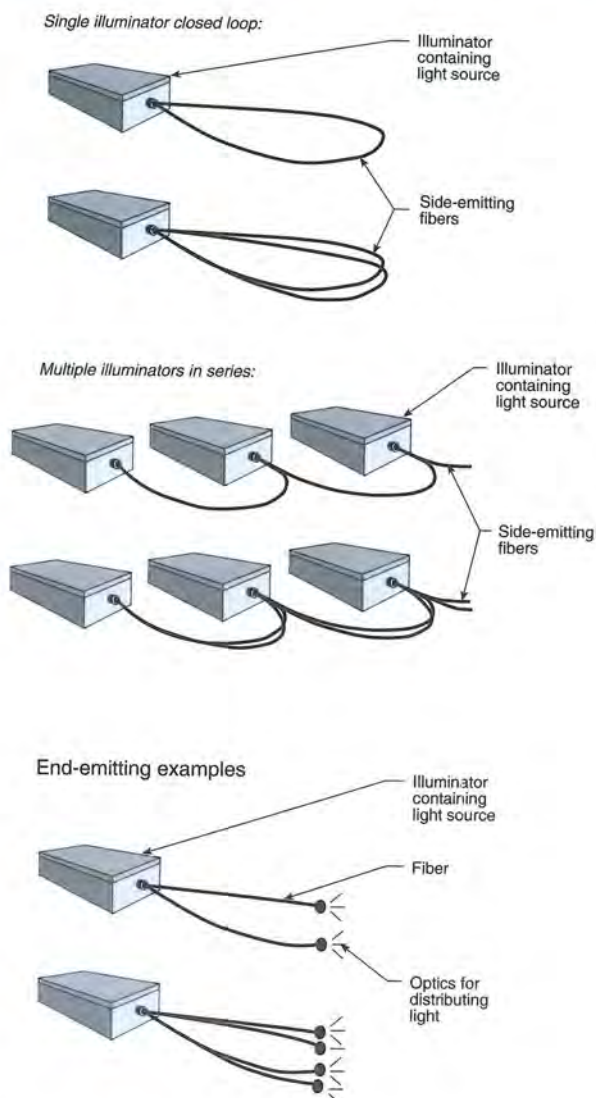


Figure 7-12. Fiber-optic luminaires.

The NEMA Classification System. This system is based on the distribution of flux within the beam produced by the luminaire. It is used primarily for sports lighting and flood-lighting luminaires. Seven distributions are defined, types 1 through 7, from narrowest to widest beams (see Figure 20-10 in Chapter 20, Sports and Recreational Area Lighting).

The IESNA Classification System For Outdoor Luminaires. This system is based on the shape of the area that is primarily illuminated by the luminaire. It is used for roadway and area lighting luminaires. Though these luminaires can differ in the manner in which they are mounted, by the type of intensity distribution they exhibit, and by the degree to which they provide cutoff, these luminaires often are specified by the way in which they illuminate an area.

Following are the IESNA outdoor luminaire classifications by intensity distribution (see Figure 22-6 in Chapter 22, Roadway Lighting). More detailed information on these luminaire types is found in Chapter 22, Roadway Lighting.

Name	Description of illuminance distribution
Type I	Narrow, symmetric illuminance pattern
Type II	Slightly wider illuminance pattern than Type I
Type III	Wide illuminance pattern
Type IV	Widest illuminance pattern
Type V	Symmetrical circular illuminance pattern
Type VS	Symmetrical, nearly square illuminance pattern

Cutoff classifications are as follows:

Name	Description of intensity distribution
Full cutoff	A luminaire light distribution where zero candela intensity occurs at an angle of 90° above nadir, and at all greater angles from nadir. Additionally, the candela per 1000 lamp lumens does not numerically exceed 100 (10%) at a vertical angle of 80° above nadir. This applies to all lateral angles around the luminaire.
Cutoff	A luminaire light distribution where the candela per 1000 lamp lumens does not numerically exceed 25 (2.5%) at an angle of 90° above nadir, and 100 (10%) at a vertical angle of 80° above nadir. This applies to all lateral angles around the luminaire.
Semicutoff	A luminaire light distribution where the candela per 1000 lamp lumens does not numerically exceed 50 (5%) at an angle of 90° above nadir, and 200 (20%) at a vertical angle of 80° above nadir. This applies to all lateral angles around the luminaire.
Noncutoff	A luminaire light distribution where there is no candela limitation in the zone above maximum candela.

Principal Types of Luminaires

Commercial and Residential

Portable Luminaires. These are completely self-contained luminaires designed to be moved and placed near the task to be lighted. They have a plug and outlet connection to electric power and usually contain integral switching and/or dimming. They usually contain low-wattage incandescent, tungsten-halogen, or compact fluorescent lamps. Examples of portable luminaires are floor and table luminaires, desk luminaires, and partition-mounted luminaires (Figure 7-13).

Furniture Mounted. Permanently attached to furniture or other equipment surface, these luminaires are designed to be in close proximity of the task and produce localized lighting. They can be found under kitchen cabinets and in bathroom vanities (Figure 7-14).

Recessed Downlights. These are general-purpose luminaires designed to provide general or ambient lighting in a space. They are recessed into the ceiling and are designed to produce illuminance on a floor or workplane. Certain types have concentrated luminous intensity distributions designed for spaces with computer VDTs. It is often necessary to augment these luminaires with other types that raise wall luminances and add vertical illuminance to the space. Recessed downlights can be grouped by size.

There are two types of recessed downlights (Figure 7-15). Incandescent, compact fluorescent, and metal-halide lamp downlights usually have modest apertures and can exhibit very low luminances at high viewing angles. Fluorescent lamp troffers use large fluorescent lamps and are usually used with a suspended tile ceiling system. Sizes range from 6 in. × 48 in. to 48 in. square.

Ceiling Surface Mounted. These luminaires can provide general or ambient lighting with the addition that some of the light can be emitted upward to produce a higher ceiling luminance than recessed or surface-mounted downlights. Examples include fluorescent troffers, compact fluorescent

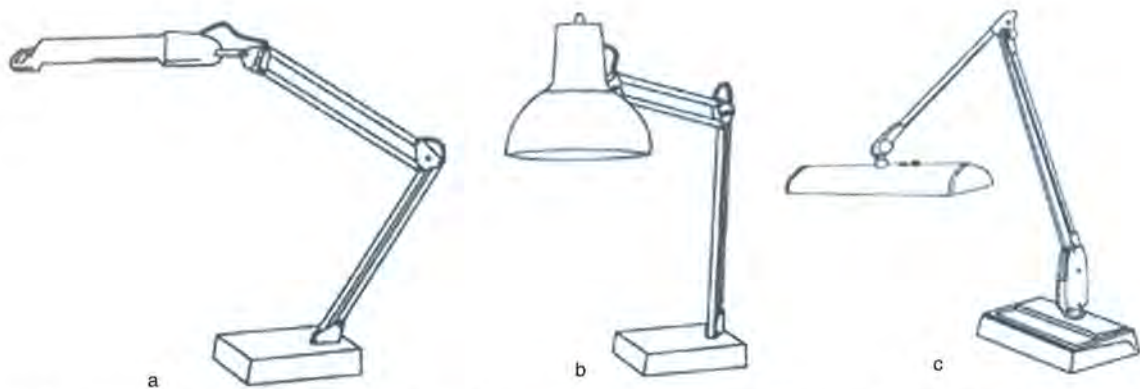


Figure 7-13. Examples of portable luminaires using (a) compact fluorescent lamp, (b) incandescent lamp, and (c) straight fluorescent lamps.

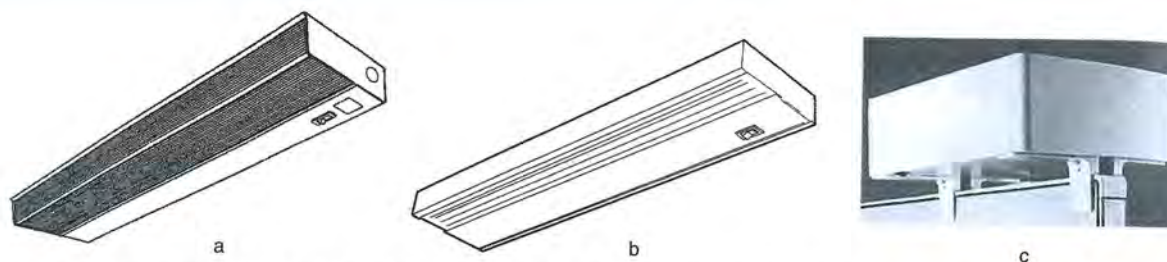


Figure 7-14. Examples of furniture-mounted luminaires: (a) under-cabinet luminaire with wrap-around prismatic lens, (b) under cabinet luminaire with extruded lens, and (c) partition-mounted luminaire with metal halide lamp.

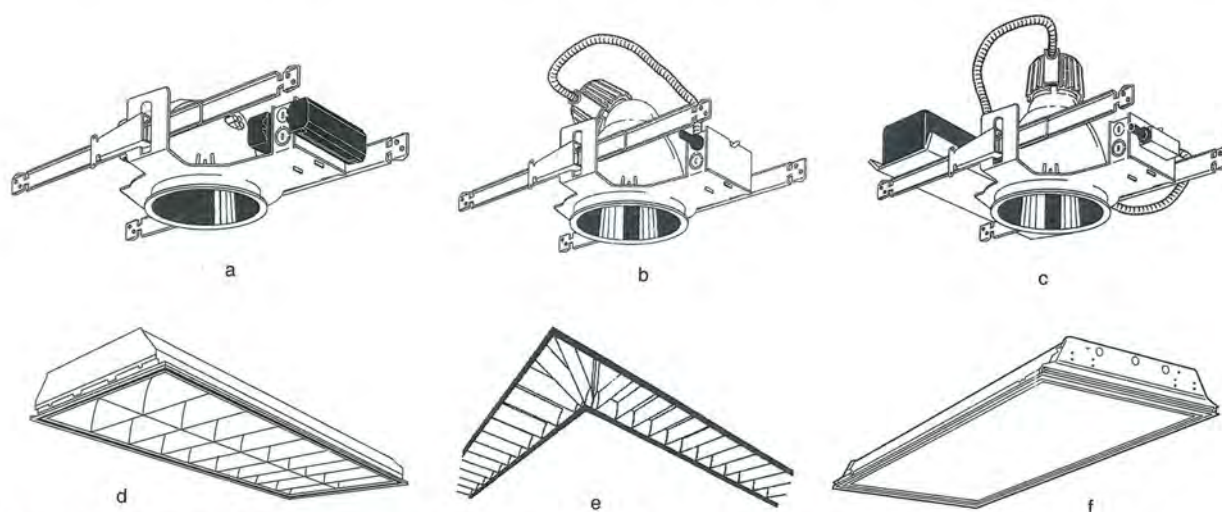


Figure 7-15. Examples of downlight luminaires using (a) compact fluorescent, (b) incandescent, and (c) metal halide lamps; (d) fluorescent lamp recessed troffer with parabolic louvers; (e) continuous linear; and (f) fluorescent lamp recessed troffer with prismatic lens.

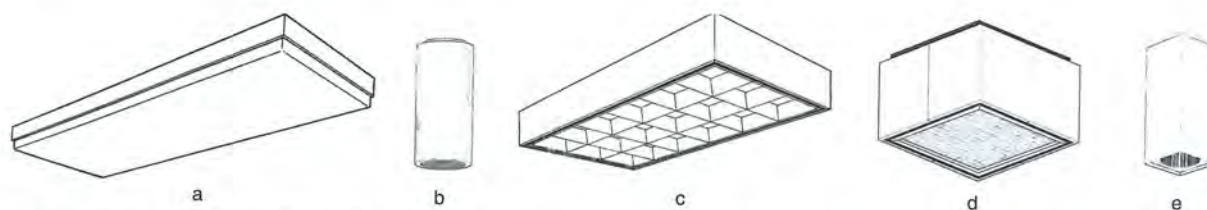


Figure 7-16. Examples of ceiling surface mounted luminaires; (a) wrap-around lens, (b) incandescent lamp downlight, (c) troffer, (d) metal halide lamp area light, and (e) metal halide lamp downlight.

downlights, incandescent and tungsten-halogen downlights for task lighting on kitchen counter tops, and wrap-around lens luminaires (Figure 7-16).

Wall Washer. These luminaires are used to produce a distribution of illuminance/luminance on a wall that, though not necessarily uniform, changes gradually from high values at the top of the wall to lower values down the wall. Many wall-wash luminaires are designed to achieve an illuminance ratio from the top to the bottom of the wall of 10:1 or

less. Wall-wash luminaires can be recessed or surface mounted. These can be grouped by size.

There are two basic types of wall washers (Figure 7-17). Linear fluorescent wall washers usually have a reflector that allows them to be placed close to the wall, and are available recessed or surface-mounted. Other wall washers, including compact fluorescent, incandescent, halogen, or compact metal halide lamp luminaires, are smaller units that, if recessed, have a modest aperture and therefore can appear like

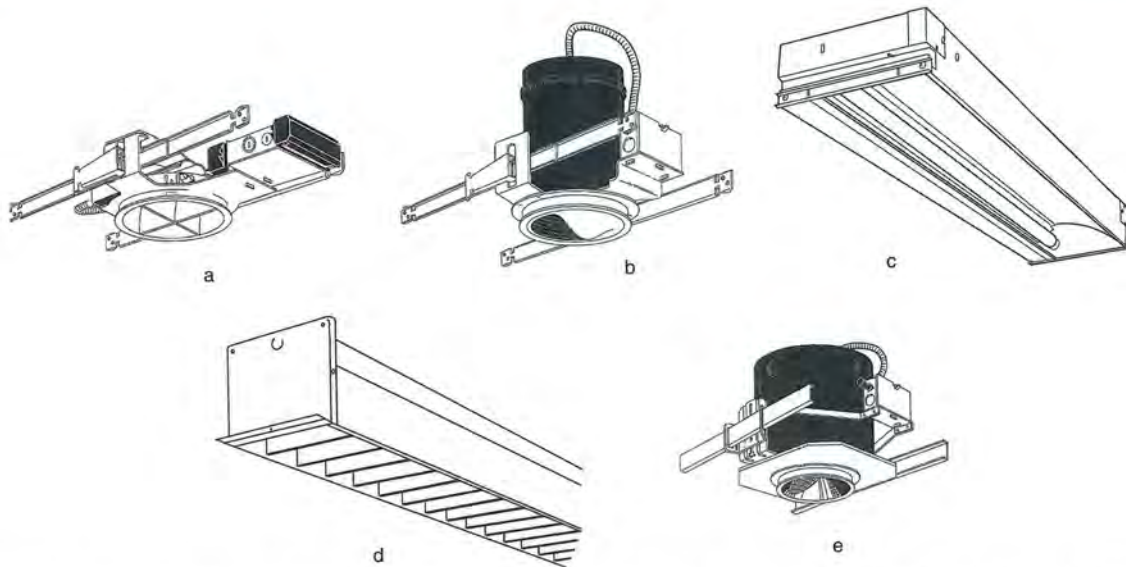


Figure 7-17. Examples of wall-wash luminaires: (a) compact fluorescent lamp luminaire with baffles, (b) incandescent lamp luminaire with eyelid, (c) recessed linear fluorescent lamp, (d) continuous linear fluorescent lamp with baffles, and (e) incandescent lamp wall washer with spread lens.

other downlights in the space. They also can be surface mounted.

Accent. These luminaires are either themselves ornamental or are designed to produce patterns of light that are ornamental. They can be ceiling recessed or surface mounted, or wall mounted (Figure 7-18).

Ceiling-mounted accent luminaires use incandescent, tungsten-halogen, compact fluorescent, or low-wattage metal halide lamps. The lamps are adjustable or fixed.

Sconces and other wall-mounted accent luminaires use incandescent, tungsten-halogen, or compact fluorescent lamps. Since they are often mounted low, they are often in the field of view, and therefore the designer should be aware of the potential for glare. Translucent shields, which vary in size or shape, are often used for lighting hallways, stairways, doorways, and mirrors.

Wall-mounted luminaires with opaque shielding completely conceal the source from normal viewing angles and are strongly directional in light distribution. Downlight luminaires often are mounted on the wall for accent and display lighting, whereas uplight luminaires can be used for general, indirect lighting. The extent to which wall-mounted luminaires protrude from the wall is often subject to code restrictions such as the Americans with Disabilities Act.¹

Track. This refers to a system that includes luminaires and a track or rail that is designed to both provide mounting and deliver electric power (Figure 7-19). Track is generally made of linear extruded aluminum, containing copper wires to form a continuous electrical raceway. Some varieties can be joined or cut, and others set into a variety of patterns with connectors. Track is available in line or low-voltage,

with remote transformers available for the low-voltage equipment.

Track can be mounted at or near the ceiling surface, recessed into the ceiling with special housing or clips, or mounted on stems in high-ceiling areas. It also can be used horizontally or vertically on walls. Mechanical considerations may limit certain mounting arrangements, particularly for wall-mounted installations. Track can be hardwired at one end or anywhere along its length. Flexibility can be added with a cord-and-plug assembly to supply power rather than with hardwiring.

A variety of adjustable track-mounted luminaires are available for attachment at any point along the track. These luminaires come in many shapes and styles, housing a large assortment of lamps, including line and low-voltage. In addition, a number of luminaires are designed to create special effects for decorative applications. Track luminaires use incandescent, tungsten-halogen, compact fluorescent, metal halide, or high-pressure sodium lamps.

Point Indirect. These luminaires are designed to provide general or ambient lighting by illuminating the ceiling with compact fluorescent, metal halide, or even high-pressure sodium lamps (Figure 7-20). They contain reflectors that help produce a wide distribution so that they can be mounted close to the ceiling. Pendants or cable usually suspends them, but some types are post-mounted from the floor.

Linear Indirect. These luminaires are designed to use linear or compact fluorescent lamps to provide general or ambient lighting by illuminating the ceiling (Figure 7-20). Reflectors are used to produce wide distributions and permit short suspension distance. Linear indirect luminaires can be

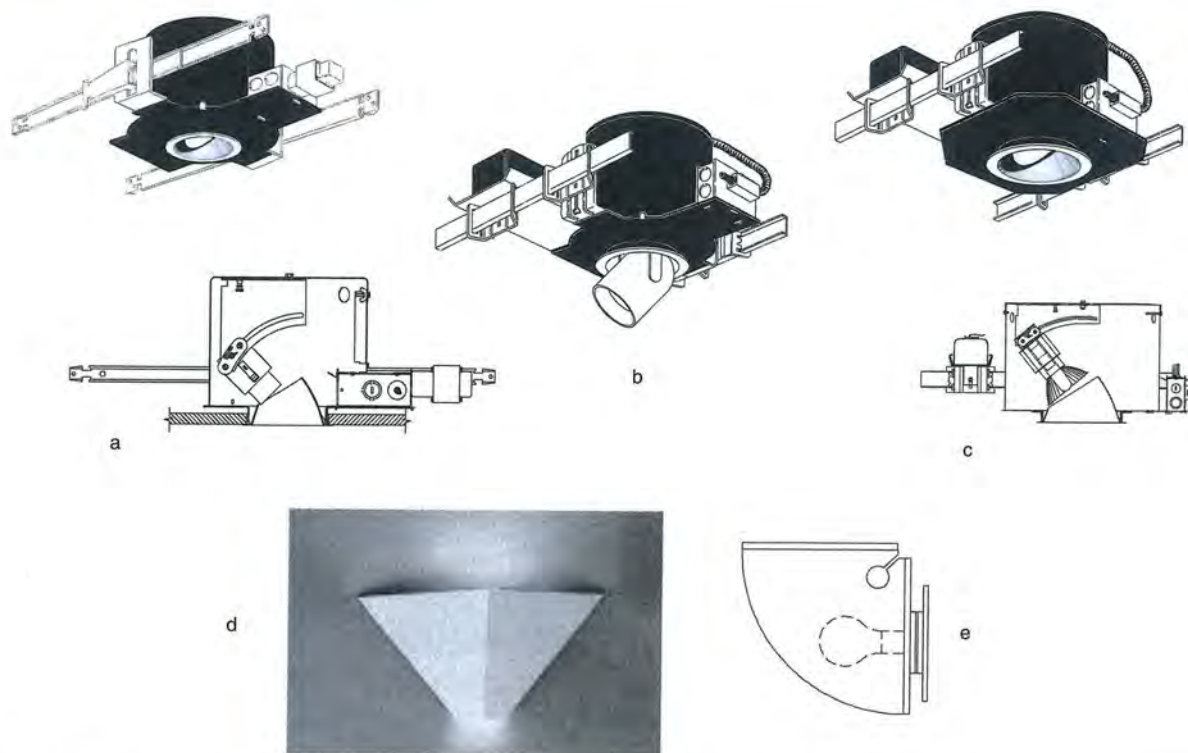


Figure 7-18. Examples of accent luminaires: (a), (b), and (c) recessed adjustable accent luminaires for reflector incandescent lamps, for tungsten-halogen lamps, and HID lamps; (d) and (e) front and side view of wall sconce luminaires using compact fluorescent and incandescent lamps.

suspended from the ceiling by pendants or cable or, in the case of modest spans, mounted by their ends. They can also be mounted on the walls to form a perimeter lighting system. Suspended linear indirect luminaires usually have a luminous intensity distribution that is symmetric about the lamps' axis, whereas wall-mounted linear indirect luminaires typically have an asymmetric distribution.

Linear Direct-Indirect. These luminaires are similar to the suspended indirect but provide some downward directed light. Variations are available for changing the proportion of upward and downward light.

Cove. These luminaires are designed to be placed in an architectural cove or to have a shape such that when mounted on the wall they produce a cove and its lighting effect (Figure 7-21). The simplest form of this luminaire is a fluorescent lamp strip, providing ballast and lamp sockets. More elaborate forms provide reflectors to control near-wall and ceiling luminance.

Stage. These luminaires are designed to produce tight optical control and provide maximum flexibility (Figure 7-22). They are common in theaters and television studios for lighting stage sets and people.



Figure 7-19. Examples of track luminaires: (a) close-up of multicircuit track, (b) and (c) track-mounted luminaires with optical control, and (d) and (e) track luminaires for holding and aiming lamps.

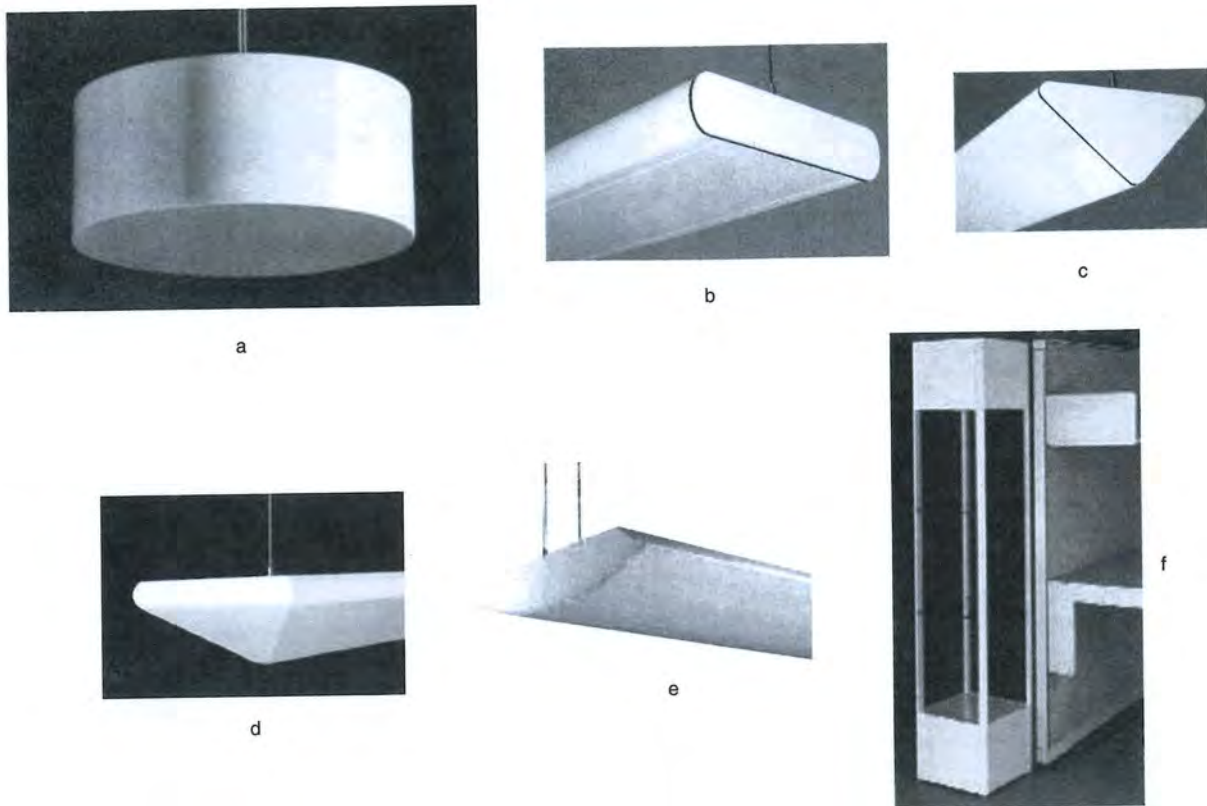


Figure 7-20. Examples of indirect luminaires: (a) pendant-mounted point indirect luminaire with metal halide lamp, (b) and (c) linear two-lamp fluorescent indirect luminaires, (d) linear single fluorescent indirect luminaire, (e) linear two-lamp fluorescent luminaire, and (f) floor-mounted point indirect luminaire.

Industrial

Linear Fluorescent. These luminaires are often designed for high-output fluorescent lamps, with the reflector often being part of the housing (Figure 7-23). A refractor or lens is uncommon. These luminaires are designed to minimize accumulation of dirt by providing for convection; in areas with large amounts of airborne particles, dust-tight covers are used. Diffusers with gasketing are often used in wet locations.

Strips. These luminaires have one or more fluorescent lamps mounted to a small housing large enough to hold ballasts and sockets (Figure 7-24). Reflectors are uncommon since these luminaires are used in areas where a large amount of general diffuse lighting is required and efficiency and budget are a concern.

High Bay. These luminaires use HID lamps to produce general lighting in an industrial area (Figure 7-25). They are for applications with spacing-to-mounting height ratios of up to 1.0. They are surface or pendant mounted, depending on

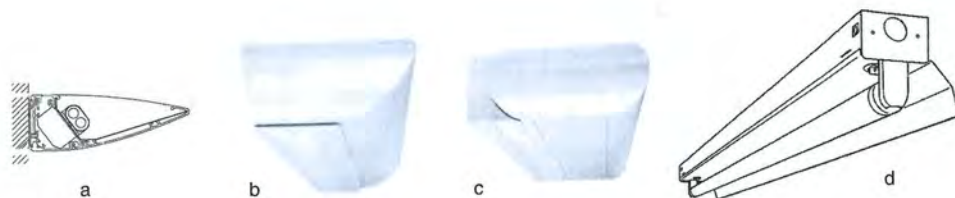


Figure 7-21. Examples of cove luminaires: (a) cove forming luminaire with biaxial fluorescent lamp, (b) and (c) cove forming luminaires with linear fluorescent lamps, and (d) fluorescent lamp strip luminaire with asymmetric reflector for mounting in a cove.

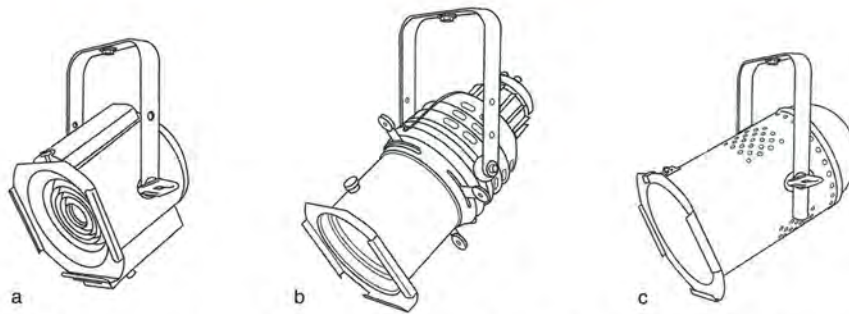


Figure 7-22. Examples of theatre luminaires: (a) Fresnel spot, (b) ellipsoidal spot, and (c) border spot.

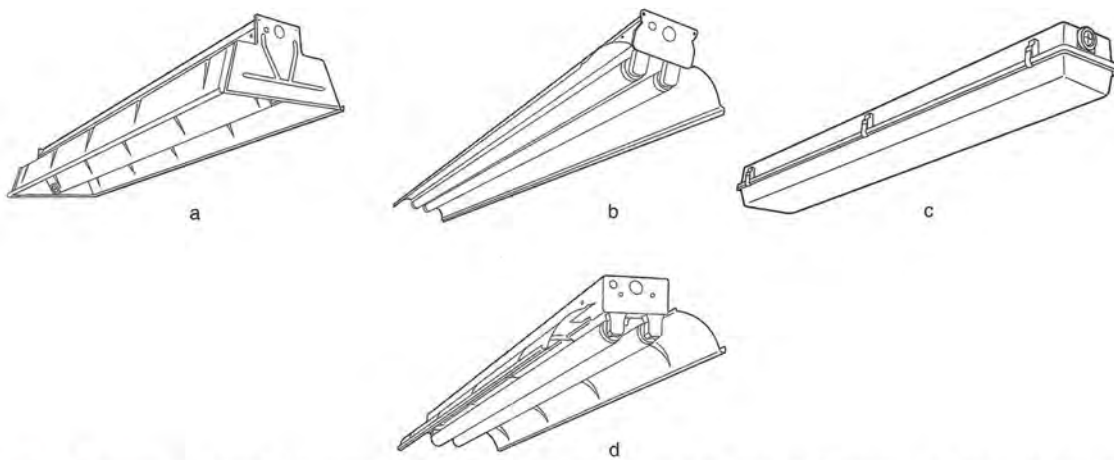


Figure 7-23. Examples of linear fluorescent lamp industrial luminaires with (a) parabolic reflector, (b) specular reflector and shield, (c) diffuser and gasketing for wet locations, and (d) open enamel reflector.

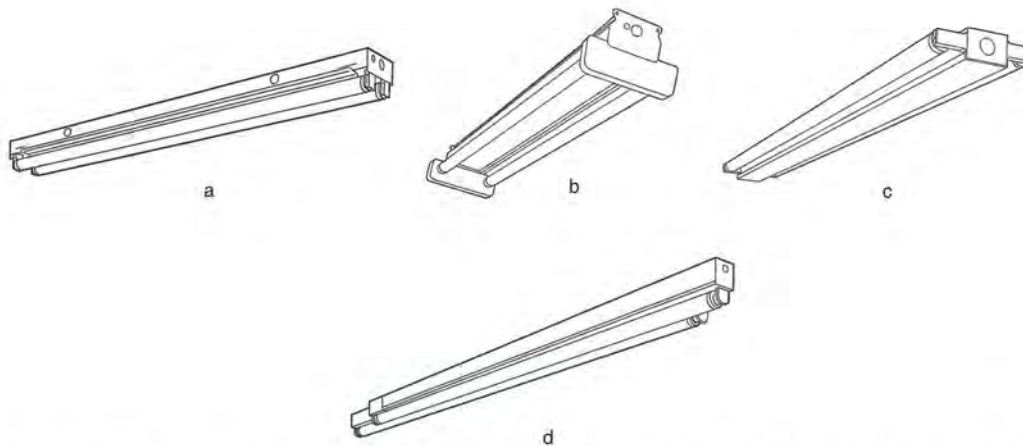


Figure 7-24. Examples of fluorescent lamp industrial strip luminaires: (a) tandem lamp strip, (b) two-lamp channel strip, (c) side-mounted lamps, and (d) staggered lamps for continuous row applications.

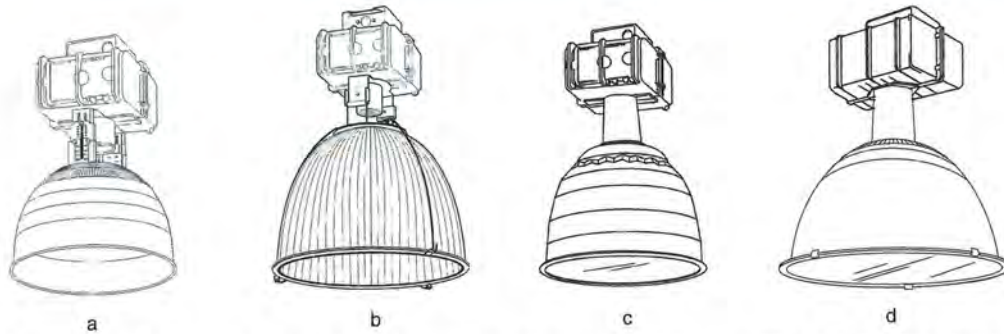


Figure 7-25. Examples of high-bay industrial luminaires: (a) open metal reflector, (b) open injection molded acrylic reflector/refractor, and (c) and (d) enclosed reflector.

the structure and openness of the area. These luminaires use reflectors and refractors to produce luminous intensity distributions that vary from narrow to wide, depending on the application and the need for vertical illuminance.

Low Bay. These luminaires use HID lamps to produce general lighting in an industrial area (Figure 7-26). They are for applications with spacing-to-mounting height ratios greater than 1.0. As with high bay luminaires, they are surface or pendant mounted. These luminaires usually have wide luminous intensity distributions to provide greater horizontal and vertical illuminances in areas with restricted ceiling heights.

Emergency and Exit. Emergency lighting luminaires are designed to provide enough light for egress in emergent situations. They may operate from power provided by batteries. Under normal conditions the batteries are continuously charged from line voltage. These luminaires contain circuitry that turns them on whenever line voltage is not present. Some HID luminaires contain auxiliary light sources that provide light while HID lamps cool off and restrike when line voltage is temporarily disrupted.

Exit luminaires help building occupants identify directions to an exit. They can be considered a type of illuminated signage that is useful under normal conditions but designed to provide critical help in emergent situations. Like emergency lighting luminaires, exit luminaires often operate on

batteries. Compact fluorescent lamps and light-emitting diodes are commonly used in exit luminaires. Examples of emergency and exit luminaires are presented in Figure 7-27.

Outdoor

Floodlight. These luminaires are often used for building lighting and other special applications (see Chapter 20, Sports and Recreational Area Lighting, and Chapter 21, Exterior Lighting). These applications can require luminous intensity distributions that range from very narrow to very wide, depending on the angular size of the object being illuminated and the effect to be achieved. The luminous intensity distributions usually are not symmetric. Most types of HID lamps are used in floodlight luminaires. Lamp orientation and reflector arrangement normally determine beam characteristics. Examples of floodlight luminaires are presented in Figure 7-28.

Exterior building lighting uses luminaires with narrow and wide distributions, depending on the portion of the building being illuminated and its distance from the luminaire mounting location. Column lighting, accent lighting and distant mounting locations require narrow distributions. Lighting large areas with near mounting locations requires very wide distributions. Floodlight luminaires often have luminous intensity distributions that produce a square or rectangular illuminance pattern (see Chapter 21, Exterior Lighting).

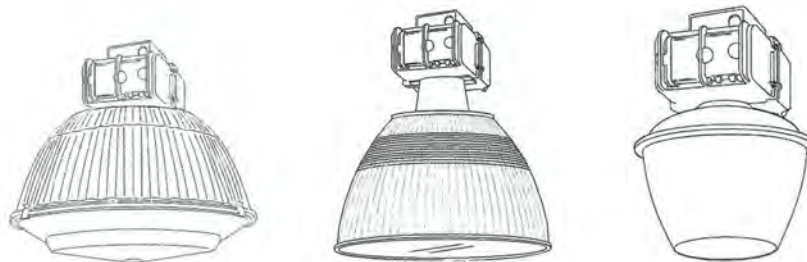


Figure 7-26. Examples of low-bay industrial luminaires.

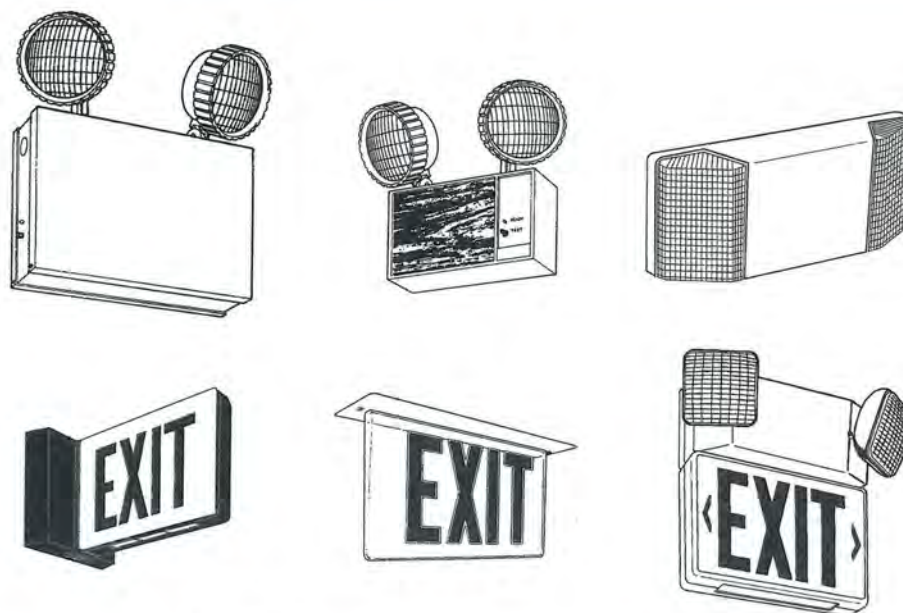


Figure 7-27. Examples of emergency and exit luminaires.

Sports Lighting. Some sport lighting luminaires have very narrow luminous intensity distributions and typically are mounted to the side and well above the playing area. Others have medium distributions and sharp cutoff and are mounted over the playing area. Metal halide lamps are common for sports lighting luminaires. Reflectors are used to produce the required luminous intensity distribution. Refractors are not used. Use of the narrow-intensity-distribution luminaires almost always requires careful design to ensure proper overlapping of beams as well as proper horizontal and vertical illuminances. Since aiming is a critical part of their application, these luminaires are usually provided with special aiming and locking gear. Internal or external louvers also may be provided to control glare and light trespass and to improve observer comfort. Examples of sports lighting luminaires are shown in Figure 7-29.

Sports lighting luminaires are usually classified using the NEMA field angle designation. Seven categories from very

narrow to very wide are used to describe the luminous intensity distribution of these luminaires (see Figure 20-10 in Chapter 20, Sports and Recreational Area Lighting).

Street and Roadway. These luminaires are designed to produce reasonably uniform illuminance on streets and roadways. They usually are mounted on arms on a pole, or are post-top mounted. All types of HID lamps are used in street and roadway luminaires. Low-pressure sodium lamps are used only occasionally. Reflectors and refractors are used to produce the various types of luminous intensity distributions required in these applications. Wide distributions permit large pole spacing. Minimum horizontal illuminance and uniformity of horizontal illuminance are typical design criteria. For this reason, the luminous intensity distributions can sometimes have maximum values at angles above 75° from the nadir.

Luminaires with dropped-dish, or ovate, refractors are commonly used in roadway applications. Because of their

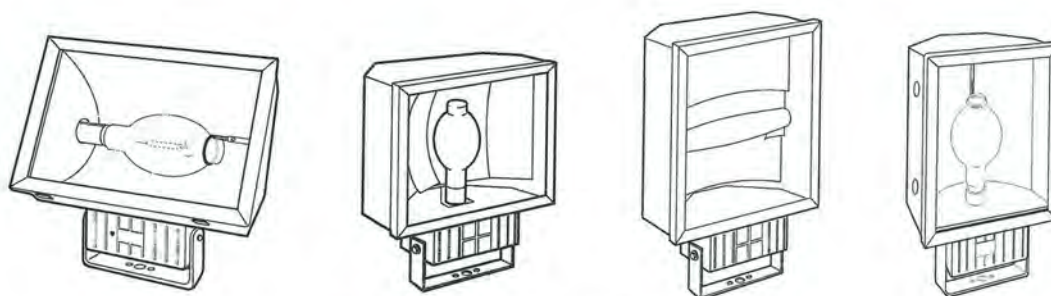


Figure 7-28. Examples of floodlight luminaires.

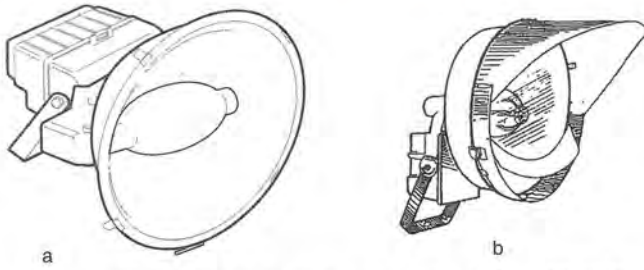


Figure 7-29. Example of sports lighting luminaires: (a) wide distribution with lamp base to the side, and (b) narrow distribution with hood and baffles to control spill light.

appearance these luminaires are referred to as “cobra head” luminaires (Figure 7-30). Poles for roadway applications are usually mounted well back from the roadside to avoid damage to both the luminaire and oncoming traffic. Modifications to the typical design of cobra heads may reduce glare and light trespass.

Pathway. Walkway and grounds lighting is often accomplished with bollards (Figure 7-31). These luminaires are mounted in the ground and have the form of a short thick post similar to that found on a ship or wharf, hence the name. The optical components are usually at the top, producing an illuminated area in the immediate vicinity. Bol-



Figure 7-30. Example of a roadway luminaire: a cobra head roadway luminaire with drop-dish refractor.

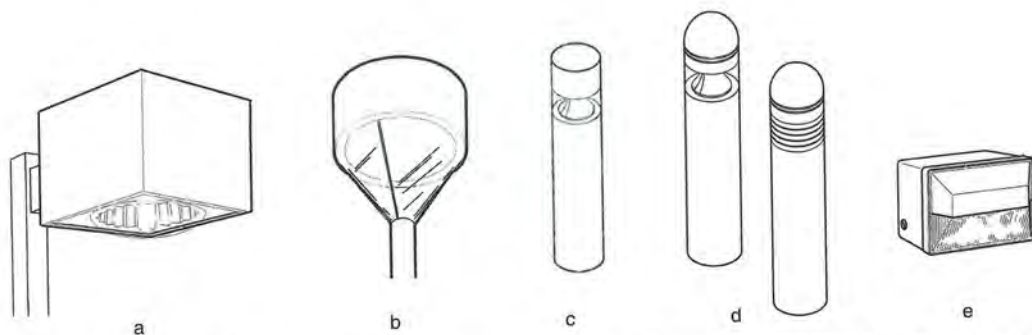


Figure 7-31. Examples of pathway luminaires: (a) and (b) post-top luminaires for pathway and area lighting, (c) and (d) bollards for pathway lighting, and (e) recessed stair and ramp luminaire.

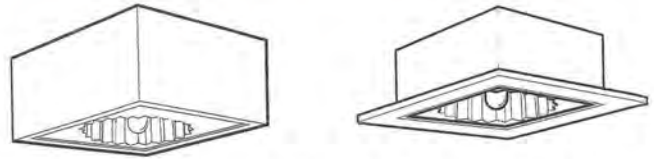


Figure 7-32. Examples of parking lot and garage luminaires.

lards are used for localized lighting. Their size is appropriate for the architectural scale of walkways and other pedestrian areas.

Small sharp cutoff luminaires are also used on small poles to provide pathway lighting. Additionally, luminaires for lighting outdoor stairs and ramps are used. These can be mounted on poles or recessed into the structure near the stairs or ramp.

*Parking Lot and Garage.*² Parking lot lighting often uses cutoff or semi-cutoff luminaires with flat-bottomed lenses. These luminaires are mounted on post-top brackets or on short arms and can be arranged in single, twin, or quad configurations. Symmetric and asymmetric intensity distributions and mounting configurations are used to provide the necessary flexibility in pole placement for parking lots. Examples of parking lot and garage luminaires are presented in Figure 7-32.

Wall-mounted luminaires are often used for small parking lots immediately adjacent to a building or in parking structures. Often referred to as “wall packs,” wall-mounted luminaires have an asymmetric distribution necessary for lighting adjacent parking lots. There is significant potential for glare and light pollution with these luminaires. Glare and light pollution can be controlled using cutoff versions of wall packs, but this decreases luminaire spacing.

Surface-mounted luminaires in parking structures are mounted on walls or ceilings. These are designed to produce a considerable amount of interreflected light in the structure.

Security. Security luminaires are typically outdoor luminaires designed to help visually secure an area. This can

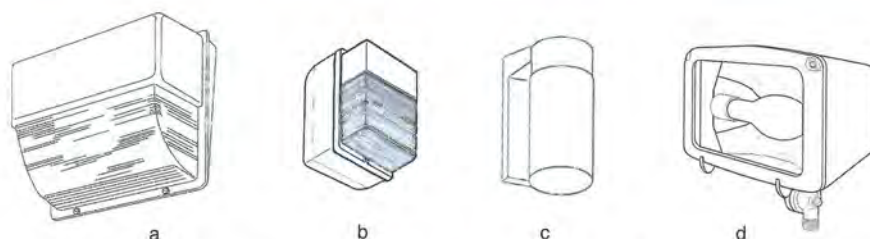


Figure 7-33. Examples of security luminaires: (a) wall-mounted HID lamp luminaire, (b) wall-mounted metal halide lamp luminaire, (c) compact fluorescent lamp jelly jar luminaire, and (d) HID lamp luminaire.

mean providing sufficient illuminance for visual surveillance or security camera surveillance. These luminaires are typically mounted in inaccessible places and have particularly strong housings and lenses to help make them vandal proof. In conjunction with some security camera systems, infrared (IR) sources can also be used that are invisible to potential trespassers. Examples of security luminaires are presented in Figure 7-33.

Landscape. Landscape luminaires are designed for use outdoors to light buildings, planting, water features, and walkways (Figure 7-34). The can be mounted in the ground, on poles, on trees, or underwater. Typically they have special housing, gasketing, lenses, and electrical wiring hardware that protects against the effects of water and corrosion.

LUMINAIRE PERFORMANCE

Luminaire performance can be considered a combination of photometric, electrical, and mechanical performance. Photometric performance of a luminaire describes the efficiency and effectiveness with which it delivers the light produced by the lamp to the intended target. This performance is determined by the photometric properties of the lamp, the design and quality of the light control components, and to some extent any auxiliary equipment required by the lamp.

The electrical performance of a luminaire describes the efficacy with which the luminaire generates light and the electrical behavior of any auxiliary equipment such as bal-

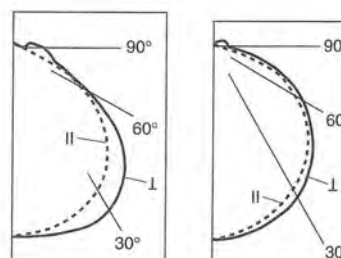


Figure 7-35. Data from an indoor luminaire photometric report. See Figure 11-12 in Chapter 11, Office Lighting, for a full indoor luminaire photometric report.

lasts. Luminaire efficacy is determined by lamp efficacy and, if present, the ballast and its interaction with the lamp. Electrical behavior, such as power factor, waveform distortion, and various forms of electromagnetic interference, are properties of the lamp and ballast.

The mechanical performance of a luminaire describes its behavior under stress. This can include extremes of temperature, water spray or moisture, mechanical shock, and fire.

Components of Photometric Performance

Luminaire Photometric Report. Luminaire photometric performance is summarized in a photometric report (Figures 7-35 and 7-36). Luminous intensity values are determined from laboratory measurements and are reported as the lumi-

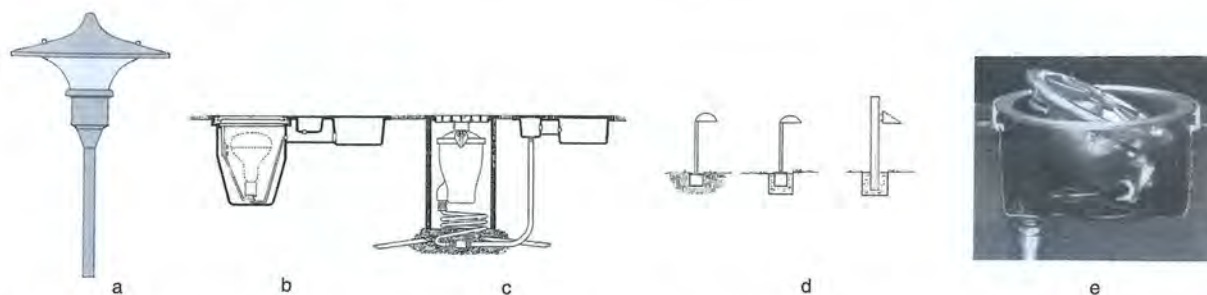
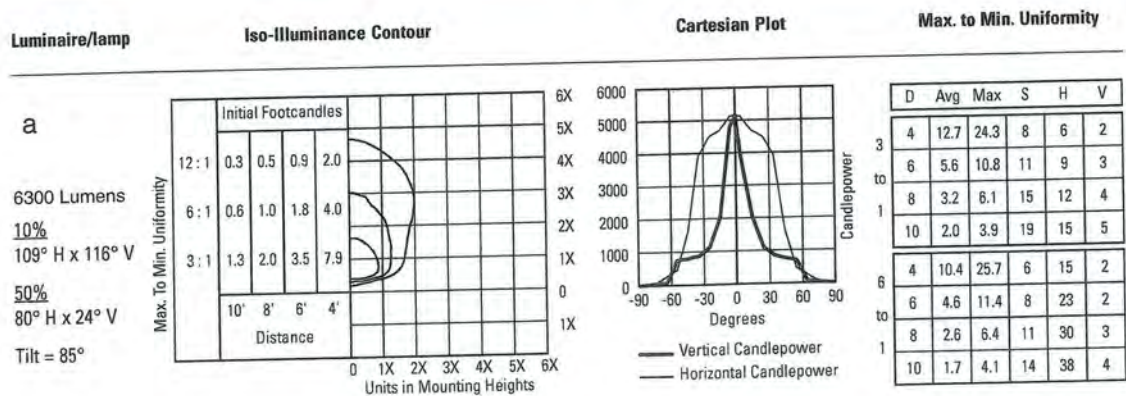


Figure 7-34. Examples of landscape luminaires: (a) ground and path luminaire, (b) and (c) direct burial and well-mounted landscape luminaires, (d) bollards for lighting pathways, and (e) underwater luminaire.



70-W High-Pressure Sodium Lamp, 5800 rated lumens

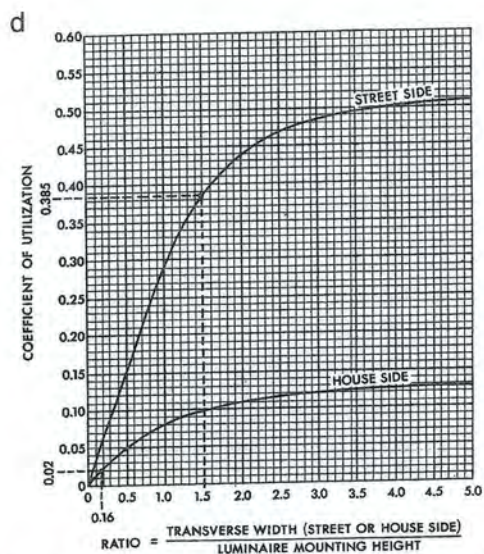
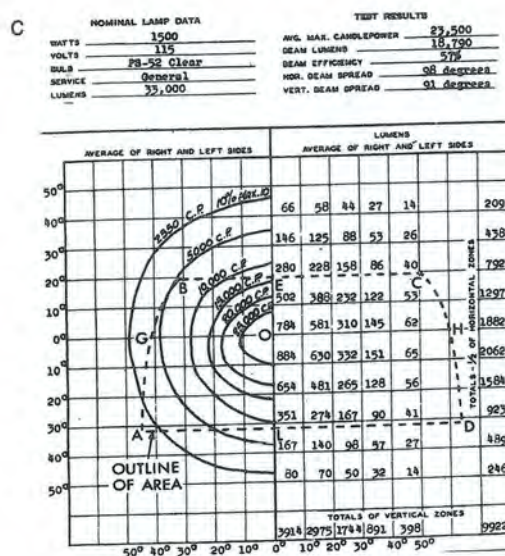
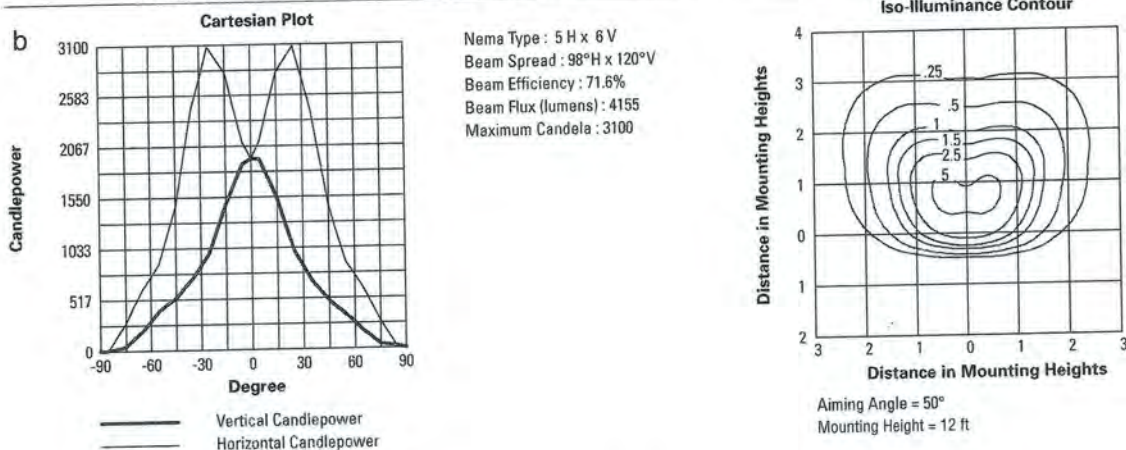


Figure 7-36. Examples of outdoor luminaire photometric reports: (a) and (b) floodlight reports, (c) zonal lumens for a floodlight, and (d) coefficients of utilization for a street lighting luminaire.

naire's luminous intensity distribution. Electrical and thermal measurements are made and often reported. These include input watts, input volts, and ambient air temperature. In addition, some calculated application quantities are usually reported. These include zonal lumens, efficiency, and coefficients of utilization. See "Luminaire Photometry" in Chapter 2, Measurement of Light and Other Radiant Energy, for a description of measurement procedures, and Chapter 9, Lighting Calculations, for a description of the calculation procedures that produce the application data.

Components of Luminaire Photometric Reports

Luminous Intensity Distribution. The luminous intensity distribution of a luminaire specifies its light distribution characteristics. Luminous intensities in various directions are specified in an angular coordinate system appropriate for the luminaire and its customary application. Most luminaires have luminous intensity distributions specified by luminous intensity values in directions given by angles in a spherical coordinate system. For indoor luminaires, the origin is down (nadir) (Figure 7-37). This is Type C photometry. The elevation (vertical) angle θ has the range $0^\circ \leq \theta \leq 180^\circ$. The azimuthal (horizontal) angle ψ has the range $0^\circ \leq \psi \leq 360^\circ$. For some outdoor luminaires, usually floodlights, the origin is the primary aiming axis (Figure 7-38). This is Type B photometry. In this case the range of the two angles is -90° to 90° .

For indoor luminaires, the range of elevation (vertical) angles, θ , depends on the distribution of the luminaire. The range is usually $0^\circ \leq \theta \leq 90^\circ$, $90^\circ \leq \theta \leq 180^\circ$, or $0^\circ \leq \theta \leq 180^\circ$, depending on whether the luminaire emits light only downward, only upward, or both. Increments of 5° in θ are usually reported, though smaller steps are usually measured and sometimes reported if the luminous intensity distribution changes rapidly with elevation angle.

Indoor luminaires that exhibit axial symmetric distributions have luminous intensity reported for $\psi = 0^\circ$. An incandescent downlight with lamp base up is a luminaire with an axially symmetric distribution. If the luminaire exhibits

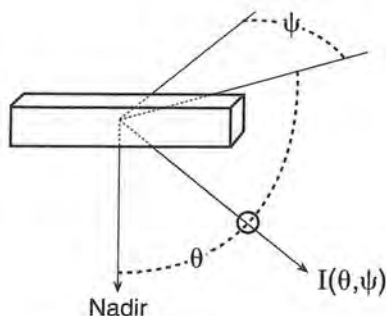


Figure 7-37. Coordinate system for indoor luminaire photometry; Type C.

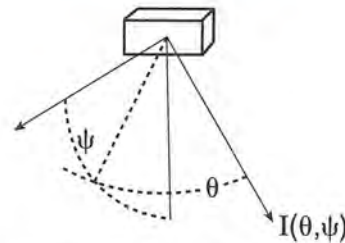


Figure 7-38. Coordinate system for outdoor luminaire photometry; Type B.

quadrilateral symmetry in the azimuthal angle, ψ , it is customary to report luminous intensity values for $0^\circ \leq \psi \leq 90^\circ$. A fluorescent troffer with a prismatic lens is a luminaire with a quadrilaterally symmetric distribution. If the luminaire exhibits bilateral symmetry in ψ , then data are reported for $0^\circ \leq \psi \leq 180^\circ$. A wall-mounted fluorescent indirect is a luminaire with a bilaterally symmetric distribution. In all cases the increments in ψ are usually 22.5° . For outdoor luminaires the range and increments are variable, the limits of each depending on the angular size of the beam.

The luminous intensity values reported for a luminaire are almost always from relative photometry, that is, lamps in the luminaires are assumed to be emitting their rated lumens. Light loss factors can be applied to account for actual field conditions.

The measurements are always far-field, that is, the distance at which measurements are made is large enough to consider the luminaire to be a point source. It is assumed that all of the luminaire lumens are emitted from the luminaire photometric center. This point is usually at the center of the opening of the luminaire, in the center of its lens, or at the geometric center of its lamps.

For many small luminaires, such as incandescent and fluorescent downlights, far-field measurements are not an issue. This is true also when the distance between luminaire and illuminated point is large compared to luminaire dimensions, as in flood lighting. But for large luminaires located near to illuminated surfaces, calculating illuminances with these luminous intensity values must be done with care. Examples of this situation are under cabinet luminaires or task lights. For more information see "Photometry as the Basis for Calculations" in Chapter 9, Lighting Calculations.

In either case, the luminous intensity distribution always gives a general idea of how light is distributed by the luminaire. A convenient way to convey this information graphically is to produce a polar plot of the luminous intensity values. The azimuthal (horizontal) angle in the spherical coordinate system is kept fixed and the elevation (vertical) angle is allowed to move from 0° to 90° or to 180° , with the luminous intensity value at each elevation angle being plotted. This data line represents one plane of luminous intensity distribution data. Similar data lines can be plotted for other

planes. Cutoff, uniformity of illuminance, and light patterns can be inferred from such plots.

For indoor luminaires, luminous intensity distributions are reported usually in two ways: as an array of values and as a polar plot. In the polar plot, luminous intensities in an azimuthal plane are plotted with a single line, labeled with the azimuthal angle or the plane's orientation. Each azimuthal plane is plotted as a separate line (see the polar plot in Figure 7-35). For outdoor luminaires, luminous intensity distributions are usually reported in Cartesian plots. Luminous intensities in horizontal and vertical planes are reported (see the section labeled "Cartesian Plot" in Figure 7-36a).

Average Luminance in Various Viewing Directions. The definition of luminance can be extended to determine the average luminaire luminance, L_{ave} :

$$L_{ave}(\theta, \psi) = \frac{I(\theta, \psi)}{A'}$$

where $I(\theta, \psi)$ is the luminous intensity from the entire luminaire in direction (θ, ψ) and A' is the luminous area of the luminaire visible from that direction. This luminance gives a general idea of the luminaire's luminance and appearance but is meaningful only if the luminaire is homogeneous. In this case L_{ave} can be used to assess the potential for discomfort glare.

If the luminaire exhibits large inhomogeneities in luminance, this value can significantly underestimate the luminance of some parts of the luminaire. Average luminance is reported in indoor luminaire photometric reports.

Zonal Lumens. For indoor luminaires, nested conic solid angle cones can be established with apexes at the luminaire photometric center. Given the size of these cones and the luminous intensity values in them, the number of lumens in each cone can be determined. Each cone defines a conic zone, and the lumens within each are the luminaire zonal lumens. Any azimuthal asymmetry present in the luminous intensity distribution is not apparent, since only the number of lumens in each zone is reported.

Many outdoor luminaires have intensity distributions that are very asymmetric. In terms of Type B photometry, the distribution in the vertical is very different than that in the horizontal. In addition, the change in intensity with angle can be very great, often having a gradient exceeding 1000 cd/degree. For these reasons the zones used to report zonal lumens are small and usually of different angular size in the horizontal and vertical.

Efficiency. The total number of lumens emitted by the luminaire can also be calculated from the luminous intensity distribution. Dividing this value by the total number of lumens emitted by the lamps in the luminaire gives the efficiency. This is a measure of how effectively the lamp and the reflector and/or refractor work to get the lamp lumens out of the luminaire.

Coefficients of Utilization. As described in Chapter 9, Lighting Calculations, coefficients of utilization for indoor luminaires describe the effectiveness with which the luminaire puts lamp lumens onto the horizontal workplane of a rectangular room. Tables of these values for a range of room surface reflectances and room shapes are part of a photometric report for an indoor luminaire that can be used for general or ambient lighting. The values of coefficients of utilization typically are between 0 and 1. The coefficients may be reported as decimal values, or they may be reported as integers that must be divided by 100 before being used in the lumen method to predict average illuminance.

Some indoor luminaires are not designed or intended to produce general lighting, and coefficients of utilization are not provided. Accent and wall-wash luminaires are examples.

Spacing Criterion. Spacing criterion is a low-precision indicator of how far apart general lighting luminaires can be spaced while providing acceptable uniformity of horizontal illuminance.

Glare Assessment. For some indoor, direct, general lighting luminaires, values of Visual Comfort Probability (VCP) are reported. If present, the table gives VCP values for a range of room sizes and luminaire mounting heights. VCP values are provided only for luminaires with significant down light and with luminances no higher than that produced by a fluorescent lamp. These limitations come from the limited applicability of VCP (see Chapter 9, Lighting Calculations).

Other Components. Some luminaire photometric reports provide additional information depending on the application. Examples include wall illuminances for wall-wash luminaires, iso-illuminance contours for outdoor area luminaires, and roadway coefficients of utilization for roadway luminaires (see sections labeled "Iso-Illuminance Contour" and "Max. to Min. Uniformity" in Figure 7-36).

Effects of Luminaire Photometrics

Luminaires and Their Lighting Effects. Luminaires light architecture, people, and visual tasks. Revealing architecture is often one of the most important purposes of lighting. Curves, coves, soffits, arches, vaults, coffers, and other architectural forms require light and shadow to be seen. A luminaire with the proper luminous intensity distribution is necessary for successful lighting in such cases.

Luminaires can produce patterns of light that are interesting and important to the appearance of the space being lighted. Scalloping, wall washing, and accenting are examples. A proper luminous intensity distribution is essential. Size of scallops, uniformity of wall washing, and sharpness of accenting depend on the distribution of the luminaire and to some extent on the lighted surface's texture and color.

Luminaires are also used to light visual tasks. The requirement for contrast and luminance determine the lumi-

nous intensity distribution and placement of luminaires. For direct lighting, computer VDTs usually require luminaires with a sharp cutoff luminous intensity distribution and very careful positioning if screen images are to be avoided. If sufficient contrast of glossy horizontal tasks is to be achieved, veiling reflections must be avoided. This requires light from the side. A luminaire with a wide luminous intensity distribution can be used to achieve this. For more information on lighting spaces containing VDTs, see Chapter 11, Office Lighting.

The lighting effect produced by a luminaire is determined largely by its intensity distribution. Choosing the appropriate luminaire often means choosing the appropriate intensity distribution. In a room lighted exclusively by table or floor lamps, the type of shade and location of the light sources becomes more critical. Deep, narrow, or opaque shades do not provide useful task lighting; they restrict the spread of both downward and upward light. Figure 7-39 illustrates the difference in performance between a 360-mm (14-in.) and a 410-mm (16-in.) shade. Listed here are common forms of lighting, characterized by the intensity distribution of the luminaires, their placement, and the resulting effects.

Direct Lighting. The distribution may vary from wide-spread to highly concentrated, depending on the reflector material, finish, and contour and on the shielding or optical control media employed. Concentrated distributions can cause sharp shadows.

Semidirect Lighting. The characteristics are essentially the same as for direct lighting except that the upward component tends to soften shadows and improve room brightness relationships. Care should be exercised with close-to-ceiling mounting of some types to prevent overly bright spots directly above the luminaires. Efficiencies can approach and sometimes exceed those of well-shielded direct units.

Direct-Indirect Lighting. Very little light is emitted at angles near the horizontal. Since this characteristic results in

lower luminances in the direct-glare zone, direct-indirect luminaires are usually more suitable than general diffuse luminaires, which distribute the light almost equally in all directions.

Indirect Lighting. In a well-designed installation the entire ceiling becomes the primary source of light, and shadows in the space are virtually eliminated. Also, since the luminaires direct very little light downward, both direct and reflected glare are minimized if the installation is well planned. It is also important to suspend the luminaires a sufficient distance below the ceiling to obtain reasonable uniformity of ceiling luminance without excessive luminance immediately above the luminaires.

Semi-Indirect Lighting. The characteristics of semi-indirect lighting are similar to those of indirect systems except the downward component usually produces a luminaire luminance that closely matches that of the ceiling. However, if the downward component becomes too great and is not properly controlled, direct or reflected glare may result. An increased downward component improves the utilization of light over that for indirect lighting. This factor makes higher illuminances possible with fewer semi-indirect luminaires and without excessive ceiling luminance.

Luminous Intensity Distribution Forms and Resulting Effects. Depending on the intended application and the lamp used, luminaires can have luminous intensity distributions that range from the completely nondirectional or diffuse, through wide- and narrow-spread distributions, to very narrow beams. Between these extremes are distributions for uniformly illuminating horizontal surfaces, producing a smooth gradient of luminance on a wall, or producing a high-luminance scallop on a wall. Some luminous intensity distributions are asymmetric as in the case of a wall washer, where more light is sent to illuminate the wall than the

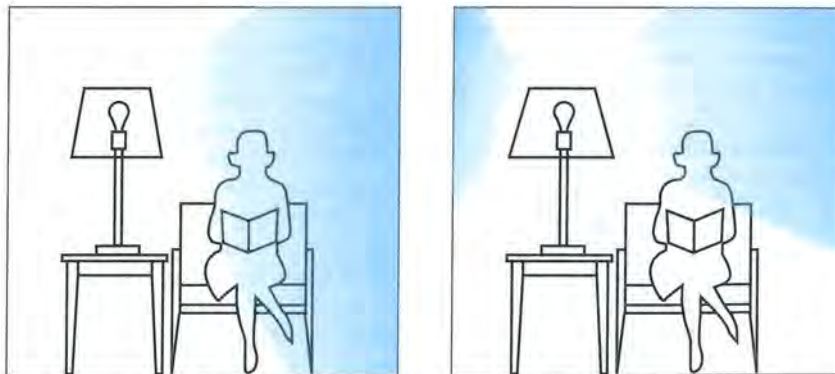


Figure 7-39. Influence of shade dimensions on light distribution of portable luminaires. Shade on the left is 360 mm (14 in.) wide. Shade on the right is 410 mm (16 in.) wide.

room. Figures 7-40 through 7-46 give examples of luminaires, luminous intensity distributions, and the illuminances and luminances they produce. In each case, the effect of only a single luminaire is shown. The calculations for these tables assume that the intensity distribution across the luminous area of the luminaire is uniform (see Chapter 9, Lighting Calculations).

Indoor luminaires are depicted in Figures 7-40 through 7-45. For these luminaires, the horizontal illuminance is that produced in the middle of a small room ($6\text{ m} \times 6\text{ m} \times 3\text{ m}$) with typical reflectances of 0.80, 0.50, 0.20 for the ceiling, walls, and floor respectively. For the horizontal illuminance the luminaire is in the center of the room. For the vertical illuminance, the luminaire is placed close to one wall. In both cases, room surface luminances are calculated and displayed as a computer-generated image of the room. These depictions are not meant to show a luminaire in its intended mounting, but rather to show the nature of its intensity distribution. Outdoor luminaires are depicted in Figure 7-46. In this case the illuminated area is $15\text{ m} \times 15\text{ m} \times 15\text{ m}$ and some of the reflectances of the surfaces are zero.

Thermal Performance of Luminaires

In general, the thermal performance of luminaires cannot be isolated from the way in which they are used. In most interior applications and some exterior applications, luminaires are thermally coupled to their environment. However, there are some thermal issues that can be essentially isolated. Three of these are the effect of the luminaire on the operating temperature of the lamp, the effect of lamp heat on luminaire materials, and the effects of air handling.

Lamp Operating Temperature. The performance of many lamp types is dependent on the bulb wall temperature. This is particularly true for fluorescent lamps, for which both light output and electrical power input—and thus luminous efficacy—vary with the temperature of the coldest spot on the bulb wall. The lamp temperature in turn is a function of the heat balance between the lamp and its surroundings. Electrical energy provided to the lamp is partly converted into light, the balance being dissipated through the mechanisms of thermal (infrared) radiation, convection, and conduction.

Even the most efficient lamps convert only a moderate percentage of their electrical power input into visible light, as shown in Figures 7-47, 7-48, and 7-49. The efficacy varies from a low of 10% for incandescent lamps, to approximately 19% for fluorescent lamps, to a high of 28% for low-pressure sodium lamps. With the exception of low-pressure sodium lamps, the greatest percentage of energy converted by most lamps is dissipated as infrared radiation. The relative energy dissipation by convection and conduction depends on airflow conditions and the temperature around the lamp, and on the details of the lamp mounting and luminaire design.

Effects on Luminaire Materials. Since lamps emit energy at infrared as well as visible wavelengths, it is useful to examine the radiant properties of materials used in luminaires. The transmittance and reflectance of most materials are wavelength dependent. Thus, for example, a lens material can be selected that has high visible transmittance but low infrared transmittance, thereby reducing the amount of heat radiated from the luminaire. However, the heat that is trapped in the luminaire causes the lamp temperature to be greater than it would be otherwise. This may be desirable if higher lamp temperatures are needed to boost efficiency, but consideration should be given to the possibility of increased thermal stresses within the luminaire. Figure 7-50 lists the radiant properties of several materials that are commonly used in lighting systems, including the percentage reflectance and transmittance at selected wavelengths.

Air Handling. The thermal performance of an indoor luminaire can also include its ability to deliver or extract air from a space. These heat-transfer luminaires often are referred to as air-handling luminaires and are constructed to add or remove heat from a space by moving air. They are constructed to minimize the effect of the air on the lamp bulb temperature.

Testing and Compliance

Luminaires should be installed in accordance with regional safety regulations and be certified for safety by an organization that is accredited in the region in which the luminaire is installed. National and local electrical codes sometimes determine the type of lighting equipment that can be used and the method of installation. Typically, luminaires are tested in accordance with national or international safety standards. These establish a minimum level of safety to reduce the likelihood of fire or electric shock.

United States. Luminaire installation practices in the United States are dictated by the National Electric Code (NEC),³ which is sponsored by the National Fire Protection Association. This code is revised every three years. The NEC requires that equipment be listed as meeting minimum safety standards by an organization that is acceptable to the municipal authority having jurisdiction over the installation. This authority is typically the local electrical inspector. The American National Standards Institute (ANSI) has accredited Underwriters Laboratories (UL) as the standards-making organization for luminaires in the United States. Virtually all local authorities require luminaires to be UL listed. They sometimes require other certifications as well.

The Occupational Safety and Health Administration (OSHA) accredits some laboratories to evaluate products using ANSI/UL standards. Such a laboratory is designated as a National Recognized Testing Laboratory.

Canada. Luminaire installation practices in Canada are dictated by the Canadian Electric Code (CEC),⁴ published by

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Recessed troffer with two fluorescent lamps prismatic lens. Used for general lighting.					
Recessed troffer with two fluorescent lamps and louvers. Sharp cutoff for lighting spaces where VDTs are used.					
Downlight using a compact fluorescent lamp and baffles for general lighting.					
Downlight using a compact fluorescent lamp for general lighting.					
Downlight using a 100-W A-19 lamp for general lighting.					

"Sharp cutoff" refers to an abrupt fall off, usually to zero, of the intensity in a distribution. Essentially no light is emitted above this cutoff angle.

Figure 7-40. Interior downlight luminaire luminous intensity distributions.

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Recessed wall washer with a compact fluorescent lamp, spun reflector, and "kicker" to produce an asymmetric distribution.					
Ceiling surface-mounted linear wall washer with single fluorescent lamp.					
Recessed cove wall washer using one fluorescent lamp.					
Recessed linear wall washer using one T-8 fluorescent lamp.					
Downlight using a compact fluorescent lamp and asymmetric reflector for lighting corridors.					

Figure 7-41. Interior wall-wash luminaire luminous intensity distributions.

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Pendant-mounted linear indirect with two fluorescent lamps. Suspended 0.3 m from ceiling.					
Pendant-mounted linear indirect with two fluorescent lamps. Suspended 0.6 m from ceiling.					
Linear cove mounted with one fluorescent lamp. Suspended 0.6 m from ceiling.					
Pendant-mounted indirect with one 175-W metal halide lamp. Suspended 0.6 m from ceiling.					

Figure 7-42. Interior indirect luminaire luminous intensity distributions.

the Canadian Standards Association (CSA). This code is revised every five years. The CEC requires that equipment be submitted for examination and testing by an acceptable certification agency. The CSA is the standards-making organization for luminaires in Canada. The Standards Council of Canada accredits laboratories in Canada to evaluate lumi-

nares using CSA standards. The accredited laboratory labels equipment that meets these standards.

Mexico. Luminaire installation practices in Mexico are dictated by the Mexican government through a series of Mexican Governmental Obligatory Safety standards. Products

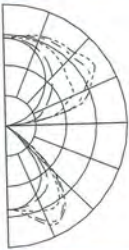
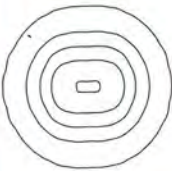
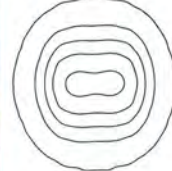
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Pendant-mounted exhibiting 70% uplight and 30% downlight. With two T-8 fluorescent lamps suspended 0.3 m from the ceiling.					
Pendant-mounted exhibiting 70% uplight and 30% downlight. With two T-5 fluorescent lamps suspended 0.3 m from the ceiling.					

Figure 7-43. Interior direct/indirect luminaire luminous intensity distributions.

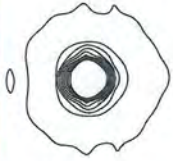
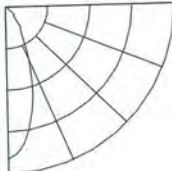
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Recessed accent luminaire mounted 0.6 m from wall with 50-W MR16 tungsten-halogen lamp.					
Track and four luminaires with 50-W MR16 tungsten-halogen lamps, having beams of 10°, 20°, 40°, and 60°, aimed at the wall.					

Figure 7-44. Interior accent luminaire luminous intensity distributions.

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Surface-mounted luminaire with reflector and two T-12 fluorescent lamps.					
Strip luminaire with two T-12 high output (HO) fluorescent lamps.					
High-bay luminaire with 400-W metal halide lamp.					
Low-bay luminaire with 400-W metal halide lamp.					

Figure 7-45. Interior industrial luminaire luminous intensity distributions.

that comply with the Mexican requirements bear the mark NOM. Laboratories are accredited by the Mexican Board of Accreditation for Testing Laboratories.

European Community. Luminaires that are exported to the European Community are required to bear the CE mark indicating that the manufacturer is in compliance with all assessment procedures required for luminaires. Essentially,

luminaires are required to comply with applicable International Electrotechnical Commission requirements.

SPECIFYING AND USING LUMINAIRES

The successful use of luminaires requires an understanding of the lighting task they accomplish and the environ-

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire Mounted Away from the Wall)	Visual Effect (Luminaire Mounted Near the Wall)
Post-top luminaire for area lighting. With 250-W metal halide lamp.					
Parking lot lighting luminaire having a sharp cutoff luminous intensity distribution. With 400-W metal halide lamp.					
Floodlight for building lighting. With beam and 400-W metal halide lamp.					
Floodlight for building lighting. Narrow beam and 400-W metal halide lamp.					

"Sharp cutoff" refers to an abrupt fall off, usually to zero, of the intensity in a distribution. Essentially no light is emitted above this cutoff angle.

Figure 7-46. Exterior luminaire luminous intensity distributions (continued on next page).

ment in which they operate. An appropriate luminaire for the lighting task has the proper photometric characteristics and is compatible with the environment. (Photometric characteristics are considered in the sections above.) Electrical, thermal, mechanical, acoustical, and maintenance aspects of a luminaire's environment can affect its performance.

Electrical

Every luminaire, as part of a lighting system, should also be considered part of an electrical wiring system. Branch-circuit panel boards and the feeders that serve them must be designed to carry the lighting electrical load. The characteristics of the electrical system, such as voltage, phases, and capacity, must be known in order to design circuits or to

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire Mounted Away from the Wall)	Visual Effect (Luminaire Mounted Near the Wall)
Cobra head luminaire for street lighting. Cutoff luminous intensity distribution, flat lens and 200-W metal halide lamp.					
Cobra head luminaire for street lighting. Drop lens and 200-W metal halide lamp.					
Sports lighting luminaire with wide beam and 1000-W metal halide lamp.					
Sports lighting luminaire with narrow beam and 1000-W metal halide lamp.					

Figure 7-46 (continued). Exterior luminaire luminous intensity distributions.

choose any controls such as switches, dimmers, or occupancy sensors.

Designers should know the fundamentals of electrical systems design to ensure that they can optimize flexibility and cost. All electrical systems in the United States must be designed and installed in accordance with the provisions and requirements of the NEC³ as well as state and local codes. To as-

sure that these requirements are met, the electrical system should always be designed by a licensed professional engineer.

The first step in the design of a coordinated lighting and electrical system is to determine the utilization voltage of the system. For new buildings, this information may be obtained from the utility company or from the engineer. In existing buildings, the information may be obtained from the

Figure 7-47. Energy Output for Some Fluorescent Lamps of Cool White Color

Type of Energy	40-W T-12	96-inch T-12 (800 mA)	PG17† (1500 mA)	T-12 (1500 mA)	T-8 F32 rare earth
Light	19.0%	19.4%	17.5%	17.5%	23.4%
Infrared (est.)*	30.7	30.2	41.9	29.5	29.0
Ultraviolet	0.4	0.5	0.5	0.5	0.4
Conduction-convection (est.)	36.1	36.1	27.9	40.3	34.2
Ballast	13.8	13.8	12.2	12.2	13.0
Approximate average bulb wall temperature	41°C (106°F)	45°C (113°F)		60°C (140°F)	37°C 99°F

* Principally far infrared (wavelengths beyond 5000 nm).

† Grooves sideways.

Note: Lamps are operated on high-power-factor, 120-V, 2-lamp ballasts under ambient temperatures of 25°C (77°F) in still air.

maintenance engineer by measurement or by reading the name plate data on existing panel boards.

The electrical characteristics most often encountered in the United States are 120/240 V, single phase, three wire for residential buildings; 120/208 V, three phase, four wire for older or small commercial buildings; and 277/480 V, three phase, four wire for many newer and large commercial buildings. In Canada, the voltages are 120/240 V, single phase, three wire for residential buildings; 347/600 V, three phase, four wire for commercial buildings; and 277/480 V, three phase, four wire for commercial buildings in some provinces and areas. In Mexico, the electrical characteristics are 127/220 V, three phase, four wire for residential and commercial buildings and 220/440 V, three phase, four wire for industrial buildings. It should be noted, however, that branch-circuit wiring for lighting in residential and commercial applications in Mexico uses 127 V, single phase.

When the engineer is faced with a 277/480-V source of power, step-down transformers (to obtain 120/208 V) are required for use with incandescent sources. The designer must exercise caution with step-down transformers because they

Figure 7-48. Energy Output for Some Incandescent Lamps

Type of Energy	100-Watt* (750-hour life)	300-Watt (1000-hour life)	500-Watt (1000-hour life)	400-Watt ‡ (2000-hour life)
Light	10.0%	11.1%	12.0%	13.7%
Infrared†	72.0	68.7	70.3	67.2
Conduction-convection	18.0	20.2	17.7	19.1

* Coiled-coil filament.

† Principally near infrared (wavelengths from 700 to 5000 nm).

‡ Tungsten-halogen lamp.

Figure 7-49. Energy Output for LPS and Three High Intensity Discharge Lamps

Type of Energy	400-Watt Mercury	400-Watt Metal Halide	400-Watt High Pressure Sodium	180-Watt Low Pressure Sodium
Light	14.6%	20.6%	25.5%	29.0%
Infrared	46.4	31.9	37.2	3.7
Ultraviolet	1.9	2.7	0.2	0
Conduction-convection	27.0	31.1	22.2	49.1
Ballast	10.1	13.7	14.9	18.2

may also be used for power to appliance and receptacle circuits, leaving little or no power for incandescent lighting. If involved in a project early enough, the designer may wish to request that a portion of the transformer capacity be held in reserve for special lighting.

The location(s) of the panel boards and transformers are probably dictated by the architecture of the building. To exemplify, a high-rise office building probably has one electrical room per floor, with vertical electrical distribution of 277/480 V and a step-down transformer for 120/208 V on each floor.

Often the lighting designer is requested to state the power density prior to the completion of the design process. There are several sources of information available to assist in obtaining an answer; they include, in addition to past experience, the NEC,³ ASHRAE/ANSI/IESNA 90.1,⁵ and state and local codes.

In response to the need for effective energy utilization, controls have become a more integral part of lighting design. Various techniques for control are at the disposal of designers. These lighting control tools include two- or three-level switching of three- or four-lamp fluorescent lighting luminaires, and photoelectric control for daylight and occupancy/motion sensors. For a discussion of control strategies see Chapter 27, Lighting Controls.

High-power-factor ballasts are recommended for compact fluorescent lamp luminaires and the use of 208 or 480 V for HID sources both indoors and outdoors. There are code restrictions on the use of 480-V lighting equipment. The importance of using high-power-factor ballasts can be demonstrated by comparing them with normal-power-factor ballasts with the help of an example. Using two 26-W quad compact fluorescent lamps operating at 120 V, the electrical characteristics and hence the electrical circuit data are as indicated in the following table:

	Normal Power Factor	High Power Factor
Ballast loss	22 W	22 W
Total fixture draw	74 W	74 W
Starting current	1.20 A	0.6 A
Operating current	1.20 A	0.6 A
Voltamperes	144 VA	72 VA

Figure 7-50. Properties of Materials Used in Luminaires (T = Percent Transmittance and R = Percent Reflectance at the Selected Wavelength)

Material	Visible Wavelengths						Near Infrared Wavelengths						Far Infrared Wavelengths							
	400 nm		500 nm		600 nm		1000 nm		2000 nm		4000 nm		7000 nm		10,000 nm		12,000 nm		15,000 nm	
	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T
Specular aluminum	87	0	82	0	86	0	97	0	94	0	88	0	84	0	27	0	16	0	14	0
Diffuse aluminum	79	0	75	0	84	0	86	0	95	0	88	0	81	0	68	0	49	0	44	0
White synthetic enamel	48	0	85	0	84	0	90	0	45	0	8	0	4	0	4	0	2	0	9	0
White porcelain enamel	56	0	84	0	83	0	76	0	38	0	4	0	2	0	22	0	8	0	9	0
Clean glass-3.2 mm (0.125 in.)	8	91	8	92	7	92	5	92	23	90	2	0	0	0	24	0	6	0	5	0
Opal glass-3.9 mm (0.155 in.)	28	36	26	39	24	42	12	59	16	71	2	0	0	0	24	0	6	0	5	0
Clear acrylic-3.1 mm (0.120 in.)	7	92	7	92	7	92	4	90	8	53	3	0	2	0	2	0	3	0	3	0
Clear polystyrene-3.1 mm (0.120 in.)	9	87	9	89	8	90	6	90	11	61	4	0	4	0	4	0	4	0	5	0
White acrylic-3.2 mm (0.125 in.)	18	15	34	32	30	34	13	59	6	40	2	0	3	0	3	0	3	0	3	0
White polystyrene-3.1 mm (0.120 in.)	26	18	32	29	30	30	22	48	9	35	3	0	3	0	3	0	3	0	4	0
White vinyl-0.76 mm (0.030 in.)	8	72	8	78	8	76	6	85	17	75	3	0	2	0	3	0	3	0	3	0

Measurements in the visible range were made with a General Electric recording spectrophotometer. The reflectance was measured with a black velvet backing behind the samples. Measurements at 1000 and 2000 nm were made with a Beckman DK2-R spectrophotometer. Measurements at wavelengths greater than 2000 nm were made with a Perkin-Elmer spectrophotometer. Reflectances in the infrared region are relative to evaporative aluminum on glass.

Although the total fixture draw remains constant, the operating current increases and therefore the voltamperes increase. The net result in this example is that using normal-power-factor ballasts allows a maximum of 13 luminaires on a 20-A, 120-V circuit. Using a high-power-factor ballast allows a maximum of 20 luminaires on the same circuit.

Caution is required in the use of square wave inverters for emergency power with high-power-factor, compact fluorescent ballasts. The power-factor-correcting capacitor used in the ballast may look like a short circuit to the square wave output of the inverter and create circuit breaker problems.

Electronic ballasts have an inherent harmonic distortion that may damage the neutral conductor(s) of the electrical system. In some cases, it may become necessary to oversize the neutral conductor. For further information on electronic ballasts, see Chapter 6, Light Sources.

Thermal

The interactions between building systems as well as the response of the building to exterior conditions and occupant activities influence the performance of each of the building components. In this regard, lighting system performance is dependent on the building's thermal environment.

The major thermal considerations related to the performance of a lighting system are the dependence of its light output and efficiency on lamp temperature, and the cooling load due to energy dissipated by it. The effects of the thermal environment on light output and efficiency fall primarily within the realm of the lighting designer; the cooling load due to lighting is of more interest to the mechanical systems designer.

Essentially all of the electrical power provided to the lighting system is dissipated into the building space as heat, with the exception of any light radiated directly out of the building through transparent surfaces. The heat gain from the lighting system either contributes to the cooling load or helps to satisfy the heating requirements, depending on the

building conditions. Most large commercial buildings have large interior heat sources, such as computers and other electrical equipment, and need to be cooled throughout the year. Exterior zones in large buildings, and smaller buildings with high ratios of surface area to volume, may require heating in winter. In buildings without air conditioning, the heat from lighting systems can overheat occupant spaces.

Lighting can account for 25 to 50% of building electrical energy usage. Electrical energy to meet the cooling loads imposed by lighting can add another 10 to 20%. Another important factor is that the time of day when the lighting load is greatest corresponds to the time of peak building cooling load demand and electric utility demand and of greatest electrical energy unit cost. Thus, any improvement in lighting system efficiency can save lighting energy, cooling energy, and energy costs and reduce cooling equipment capacity requirements.

Lighting Energy Distribution Fractions. In general, the electrical energy input to a luminaire is dissipated via the following mechanisms:

- Downward visible light
- Upward visible light
- Downward infrared radiation
- Upward infrared radiation
- Downward convection
- Upward convection
- Convection to return air
- Conduction

The magnitude of each of these components depends on the type of lamp and luminaire, the HVAC design, and the design of the building space, particularly the presence or absence of a ceiling plenum. Some of the fractions may be zero for some configurations. The table in Figure 7-51 lists typical values of the lighting energy distribution fractions for various luminaire, HVAC, and room types.⁶ In this table, all visible light output, both up and down, is lumped to-

Figure 7-51. Lighting Energy Distribution Percentages

Plenum	None	None	Static	Vented	Vented	Static
Air return	Ceiling grill or sidewall	Ceiling grill or sidewall	Ducted or lamp sidewall	Ceiling grill	Lamp compartment extract	Ducted compartment extract
Visual/room	18	18	18	18	18	18
IR/room	32	72	30	25	15	5
IR/plenum	0	0	4	9	5	5
Convection/room	40	10	42	39	0	0
Convection/plenum	0	0	3	6	59	5
Convection/return	0	0	0	0	0	54
Conduction	10	0	3	3	3	3

gether, since the split can vary greatly depending on the luminaire photometric distribution.

Several test methods have been employed to assess the total energy distribution from a particular luminaire. One involves an adaptation of photometric techniques. Two others involve calorimetry, including the use of continuous-water-flow⁷ and continuous-air-flow^{8,9} calorimeters. In one study, though procedures and equipment varied widely, the test results were of the same order of magnitude.¹⁰

Testing guides for determining the thermal performance of luminaires have been published by IESNA, the Air Diffusion Council (ADC), and the National Electrical Manufacturers Association (NEMA). The IESNA issues an approved test method that considers the effect of plenum temperature and air return on the light output. The test also provides data on the manner in which heat distribution and power input depend on the return airflow through the luminaire.¹¹

Lamp Temperature as a Function of Lighting System Design. Fluorescent lamps are widely used in commercial and industrial spaces, and their performance is strongly dependent on lamp wall temperature. The type of fixture and its location relative to supply and return air ducts influence the lamp temperature and therefore performance. A convenient way of characterizing lamp thermal performance is in terms of the elevation of lamp temperature above ambient air temperature for each luminaire and HVAC configuration. This allows the determination of the lamp temperature for any ambient air temperature by adding the lamp temperature elevation to the air temperature.

For example, an unvented four-lamp fixture with an acrylic lens usually has hotter lamps than the same fixture if vented, a similar fixture with two lamps, or a fixture with an open-cell diffuser. For each fixture type and airflow configuration, the possible lamp temperatures span a fairly narrow range, approximately 3 to 6°C. Some variation in lamp temperature can be obtained by changing the airflow rate, but this has a limited effect unless lamp compartment extract is used.

Most fluorescent lamps are designed to operate most efficiently with a minimum lamp wall temperature of about 40°C. For further information on the thermal performance of fluorescent lamps, see Chapter 6, Light Sources. A fixture with an acrylic lens operates about 6 to 8°C warmer than a similar open-cell parabolic fixture. Lamp compartment air return reduces the lamp temperature by about 4 to 6°C. A two-lamp fixture operates about 4 to 7°C cooler than a similar four-lamp fixture. Lamp temperatures are very similar with ceiling grill and side slot returns.

Figure 7-52 lists ranges of minimum lamp wall temperature elevations above ambient air temperature for various luminaire and HVAC design configurations. These values were determined from full-scale testing.⁶

Cooling Load Due to Lighting. Luminaire mounting has an important role in the distribution of thermal energy. The ASHRAE Fundamentals Handbook covers the calculation

Figure 7-52. Lamp Temperature Elevations

Number of lamps	Lamp type	Luminaire type	Air return	Temperature elevation (°C)
4	40 W	acrylic	ceiling grill	26–28
4	40 W	acrylic	lamp compartment	22–25
4	40 W	parabolic	ceiling grill	20–22
4	40 W	parabolic	lamp compartment	14–17
2	40 W	acrylic	ceiling grill	21–24
2	40 W	acrylic	lamp compartment	15–19
2	40 W	parabolic	ceiling grill	10–16
2	40 W	parabolic	lamp compartment	10–12
2	20 W	acrylic	ceiling grill	15–18
2	20 W	acrylic	lamp compartment	10–14

Note: A side slot return is similar to ceiling grill.

of the space load due to lighting for various luminaires and ventilation arrangements.¹² Figure 7-53 illustrates typical heat flows for various types of ceiling-to-luminaire relationships. The total energy distribution involves all three mechanisms of heat transfer: radiation, conduction, and convection. The illustration shows a fluorescent lamp luminaire, but HID luminaires exhibit similar patterns. The input of the suspended luminaire in Figure 7-53a would be convected and radiated in all directions, to be reflected or absorbed and reradiated. Essentially all of the input energy would remain within the occupied space.

Heat transfers from the surface-mounted semidirect luminaire in Figure 7-53b involve radiation, conduction, and convection. Assuming good contact with the ceiling, upper surfaces of the luminaire transfer energy to or from the ceiling by conduction. Since many acoustical ceiling materials are also good thermal insulators, it may be assumed that temperatures within the luminaire are elevated. Thus, lower luminaire surfaces tend to radiate and convect to the space below at a somewhat higher rate. Unless the ceiling material is a good heat conductor and can reradiate above, essentially all of the input energy remains in the space.

A different situation exists when components of the system are separated from the space. The recessed luminaire in Figure 7-53c distributes some portion of its input wattage above the suspended ceiling. The actual ratio is a function of the luminaire design and plenum and ambient conditions. For most recessed static luminaires, the ratio is very nearly 50% above the ceiling and 50% below.

Heat-transfer recessed luminaires are illustrated in Figure 7-53e. Here, the convected and radiated components to the space have been reduced considerably, while the upward energy has increased correspondingly. Under certain conditions it is possible for the space load to consist almost entirely of light energy. The majority of the power input to the luminaire is directed upward, where it can be captured by the system and be subject to some form of control. Laboratory tests conducted in accordance with IESNA procedures¹¹ provide energy distribution data for evaluative purposes.

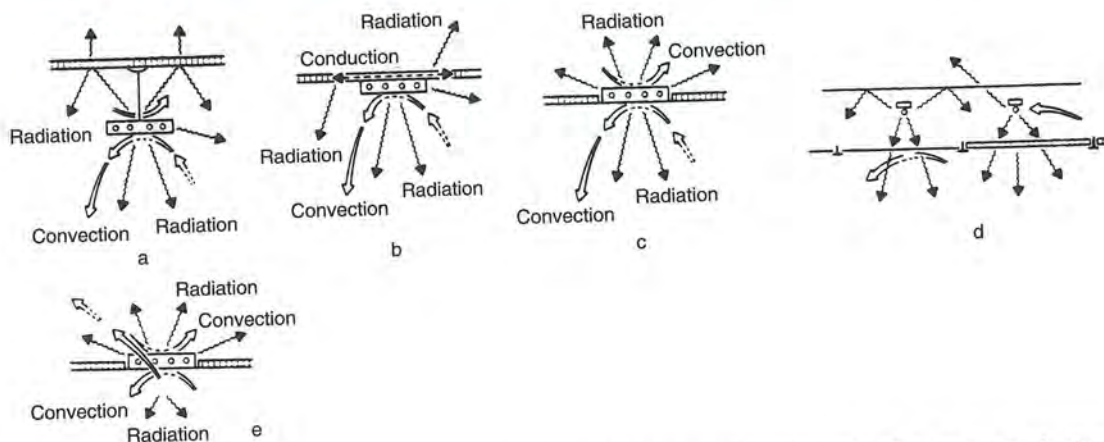


Figure 7-53. Effect of the ceiling-to-luminaire relationship on the lighting system heat transfer. The fluorescent luminaire has a direct-indirect total energy distribution classification. (a) Suspension-mounting, (b) surface mounting, (c) recessed, (d) luminous and louvered ceiling, and (e) heat transfer luminaire.

However, the total system must be evaluated, because heat removal to the plenum may raise plenum temperatures, causing conductive heat transfer back through the ceiling and floor to the space below and above, thereby adding thermal load back to the space.

Task-ambient lighting systems have a different lighting energy distribution. Care must be exercised in the selection of the cooling load factor (CLF) used in calculations of space load. Depending on the installation, it may be necessary to calculate task and ambient heat loads separately. It is possible to have both systems completely within the space. This is the case if suspended or surface-mounted luminaires are used for ambient lighting, with task lighting being incorporated into the furniture or with suspended or surface-mounted luminaires being used for both. In this case, the entire input power is an instantaneous space load.

With recessed luminaires used for ambient lighting and either suspended or furniture-mounted luminaires for task lighting, the heat loads must be figured separately, as only the task lighting load is entirely instantaneous space load. The recessed luminaire heat contribution may be considerably less, depending on the CLF.

Systems can also use recessed luminaires for both task and ambient lighting. Here, both impose a heat load that is reduced by the CLF.

Mechanical

Typically the application and environment determine the important mechanical aspects of luminaires. Ceiling-mounted luminaires must be compatible with the ceiling system, including appropriate sizes, weights, and mounting mechanisms. Luminaires intended for outdoor use should incorporate mounting and design features suitable to withstand high winds and rain and snow accumulation. Luminaires recessed in poured concrete should have an enclosure

of suitable strength, water tightness, and rigidity for the application. Surface-mounted luminaires should be strong enough so that they do not excessively distort when mounted on uneven ceilings. Suspended luminaires should have adequate strength to limit vertical sag between supports as well as lateral distortion and twist. Provision must be made for attachment of supports at suitable locations. Certain locations may require vandal-proof luminaires of heavy construction, which may in turn require additional or heavier mounting equipment. Some applications require waterproof luminaires or luminaires with housing and gasketing designed for hazardous locations. In locations that experience seismic disturbances, attention must be paid to luminaire support.¹³

Acoustical

Undesirable sound generation is sometimes a problem with fluorescent or other discharge lamps ballasted with electromagnetic or solid-state devices. Luminaires can transmit this sound to the rest of the space and, in some cases, add luminaire vibration to it. Large, flat surfaces and loose parts amplify the sound. Steps taken to minimize transmission of sound from the ballast to the luminaire may affect heat transfer characteristics.

Where luminaires are used as air supply or air return devices, the air-controlling surfaces should be designed with full consideration for air noise. In this case, there are well-accepted criteria for permissible sound levels.^{14,15}

Some ballast hum is inevitable in view of the electromagnetic principle involved, and each ballast type has a different sound rating. Where low noise levels are necessary, consideration should be given to mounting the ballasting equipment remotely or using light sources having inherently quieter operation. Remote locations of ballasts may involve complications of wiring, voltage, and thermal considera-

tions and code restrictions. Details are available in the National Electrical Code (NEC).³

Maintenance

Maintaining luminaire performance requires periodic cleaning and relamping. If luminaires are mounted in places normally out of reach, consideration should be given to how they will be accessed. If special equipment is required or if lamps are used that have a short life, luminaire placement should be reconsidered. Doors and frames should be hinged to permit easy access to the lamps and cleaning of reflectors. If luminaires are aimed, it may be necessary to specify locking hardware to prevent them from moving.

The presence of dirt and insects should be considered when choosing a luminaire. Enclosed luminaires or gasketed doors can reduce dirt and insect penetration and accumulation and reduce required maintenance.

Issues for Fiber-Optic Luminaires

Operating Temperature. The range of operating temperatures varies with the material composition of the optical fibers. The specifier must consider the range of temperatures at which the installed system operates.

Flexibility. The flexibility of an optical fiber is important in some applications. Most manufacturers specify the bend radius of their products. If a fiber is bent too sharply, tiny micro-cracks can form in the bend, which scatter some of the light into the cladding. Light may escape because the sharpness of the bend allows light to strike the core/cladding interface at unacceptable angles. Bending could also break the fiber in the sheathing, causing substantial light loss.

The bend radius is related to the diameter of the fiber. The general rule of thumb is that the minimum radius of a bend should be no less than eight to ten times the diameter of the individual fibers.

Attenuation and Light Loss in Fiber. Light transmission within a fiber is a function of length. Some light within the core is lost, and this loss is expressed in terms of attenuation in dB/m or percent loss per unit length. The attenuation of a fiber is an expression of the ratio of the light into the fiber to the light out of the fiber. Attenuation is extremely sensitive to fiber manufacturing conditions.

Attenuation also varies with the wavelength of transmitted light, an indication that the spectral composition of the light may change with transmission distance. This occurs because materials absorb the range of wavelengths associated with visible light in varying degrees and, in addition, the refractive index of a material varies slightly for each wavelength of light. As "white" light passes through a material the wavelengths separate. In fibers, these characteristics can result in the output illumination taking on coloring.

The attenuation of optical fiber restricts the maximum lengths that can be used. With minimal bending the attenua-

tion values vary from 7 to 13% per meter (2 to 4% per foot) for glass and plastic optical fiber. The length of fiber tails are limited to less than 15 m (50 ft) in most practical end light and side light applications. If side-emitting fiber is illuminated at both ends, if high luminances are not required, and if fiber attenuation is very low, runs of up to 45 m (150 ft) are possible.

Fiber Life. Theoretically, glass optical fibers last indefinitely and are generally impervious to adverse environments. Plastic fibers can yellow over time and become brittle after a number of years, particularly if subjected to UV radiation. PMMA fiber can last 10 to 15 years.

DESIGN OF LUMINAIRES

General Considerations¹⁶

Some of the factors to be considered in luminaire design include: codes and standards for their construction and installation, their physical and environmental characteristics, electrical and mechanical considerations, thermal properties, safety, and economic factors.

Reflector Design Considerations. Most lamps do not act like point sources relative to the size of the reflectors into which they are placed. Physically large arcs or coated bulbs require larger reflectors to control light to the degree obtained from small arcs or sources. Generally, the larger the source, the larger the reflector required for equivalent control.

Secondary effects of reflector or housing design can often be detrimental to the performance of a luminaire. As an example, if reflected energy is concentrated on the lamp, lamp parts may fail or lamp life may be reduced; if the beam is concentrated on a lens front, the glass may fail from thermal stress.

When fluorescent lamps are used in confining luminaires, two effects take place. The buildup of heat in the lamp compartment raises the bulb wall temperature, which may reduce the light output (see Chapter 6, Light Sources). As lamps are moved closer together, a mutual heating occurs.

Lamp Position and Replacement. The lamp operating position is important. Many lamps are designed only for base-up or base-down operation or some other specified operating position. Ignoring such limitations normally results in unsatisfactory lamp performance, reduced lamp life, or both. A basic consideration is that of easy lamp insertion and removal. Recognition should be made of possible lamp changing devices that might be used, and space should be allowed for this purpose.

Effects of Radiant Energy. Consideration must be given to the effects of lamp energy in the nonvisible regions of the electromagnetic spectrum on luminaire materials and per-

formance. Some plastics and rubber materials, for example, can be altered by UV radiation. Some reflector materials are excellent for visible light but absorb IR, thus creating thermal problems. If the intended lamp can present a hazard to people or objects under some conditions of operation (for example, some high-intensity discharge lamps operated with broken envelopes), protective devices that switch the lamp off should be designed into the luminaire or lamp.

Luminaire Efficiency. Efficiency is normally a function of physical configuration and the selection of materials used. It should be recognized that many materials change to some extent with use.

Appearance. The luminaire designer must coordinate technical, safety, and economic considerations with the final appearance. Where the lighting is primarily functional, performance has maximum importance. Design efforts generally are concentrated on reflectors, refractors, and shielding elements.

Decorative luminaires are often selected because of their appearance. In this case they may serve to complement, accent, or decorate. It may be desirable to sacrifice optimum performance in order to attain pleasing proportions and shapes. Sometimes both can be coordinated into a single luminaire.

Glare. Light sources and luminaires are potential sources of discomfort and disability glare, both indoors and out. The degree of luminance control to be designed into a luminaire depends on its intended use and the luminous environment within which it is used. Frequently, design compromises are required between visual comfort, use, and aesthetics.

Computational and measurement systems exist to evaluate the potential glare from luminaires (see Chapter 3, Vision and Perception, and Chapter 9, Lighting Calculations). They establish criteria commonly used to guide the luminaire designer in determining acceptable limits of maximum and average luminances. A thorough understanding of the principles involved is essential.

Thermal Distribution. The integration of luminaires into the air handling and architectural aspects of a building greatly in-

fluences their basic construction. Some materials used in luminaires can be good reflectors of light and good absorbers of IR radiation. For reflectance data see Figure 7-50.

Ventilation and Circulation. Air movement through the lamp compartment of a luminaire may result in the lowering of light output due to accumulation of dust and dirt, or it may maintain the lumen output by the cleaning action of air moving past the lamps.

In fluorescent lamp heat transfer luminaires a reverse air-flow is sometimes used to trap dirt and dust before it enters the lamp compartment. Consideration must also be given to the effect air currents have on bulb wall temperature, since minimum bulb wall temperature affects light output (see Chapter 6, Light Sources). Ambient temperature affects the striking voltage of all discharge lamps.¹⁷

Vibration. Incandescent lamps are normally made smaller for vibration service (up to 150 W) and for rough service (up to 500 W). Where more severe vibration is present or larger wattages are required, vibration-resisting sockets or shock-absorbing mountings may be used. For high bay mounting on a building's steel structure, a spring steel loop of proper size and tension for the luminaire's weight usually solves even the most difficult vibration problems.

High-intensity discharge lamps are less fragile than most incandescent lamps and consequently withstand more vibration. If vibration is severe, then shock absorbers should be used.

For fluorescent lamp luminaires that may be installed in vibration areas, spring-loaded lampholders should be used, rather than those of the twist type. There are conditions of very high frequencies, such as turbine deck areas, where special lampholders may be required.

Radiation Interference

Electromagnetic radiation from gaseous discharge lamps, especially of the fluorescent type, and from auxiliary components such as starters and phase control devices may be sufficient to cause interference with nearby radios, televi-

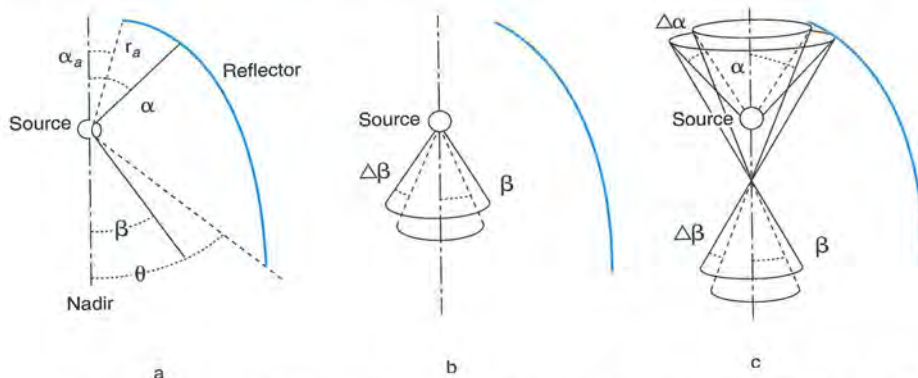


Figure 7-54. (a) Coordinate system and initial conditions for axially symmetric reflector design, (b) direct flux cone at angle β and size $\Delta\beta$, and (c) reflected flux cone from source angle α and size $\Delta\alpha$ into angle β and size $\Delta\beta$.

sion receivers, sound equipment, medical devices, radar and tracking equipment, and other sensitive electronic equipment. This interference is transmitted by direct radiation through the luminaire and by conduction through ballast and supply line.

To eliminate direct electromagnetic radiation the luminaire should be enclosed entirely with metal, except for the light-transmitting opening. Normal tolerances on the fit of parts are acceptable, but there should be no large open holes in any of the metal parts, and the electrical service should be brought in through grounded conduit or shielded cable. Proper line filters located at the luminaire can isolate conducted interference. In special cases shielded lenses over the lamps can provide additional electromagnetic radiation suppression.

Life and Maintenance. The life of any luminaire is dependent primarily on its ability to withstand the environmental conditions in which it is installed. To ensure reasonable life, appropriate treatment of all materials should be considered. Where conditions are such that electrolytic action may occur, the use of dissimilar metals and high-copper-content alloys of aluminum should be avoided where possible.

Maintenance may be a problem unless proper consideration is given to minimizing luminaire light loss factors at the time the luminaire is designed. Ventilation, gasketing, and filtering, in addition to the selection of materials to diminish the effect of dust and dirt, should be used. Ease of relamping and access to auxiliary components are important considerations as well.

Environmental Conditions

Ambient Temperature. The most obvious influence of ambient temperature is its effect on the starting and the operating characteristics of fluorescent lamps. The effect of high and low temperatures on other luminaire components should also be considered. Excess heat generated by internal heat sources such as lamps, and in some cases ballasts, must be transferred to the environment. For a discussion on the effects of temperature on lamp performance, see Chapter 6, Light Sources.

Surface-mounted luminaires and recessed equipment, especially when operating in nonventilated plenums, are often exposed to high ambient temperatures. Some industrial areas may be 65°C (150°F), or even higher. Refrigerated storage areas, and in some climates unheated storage areas, attain temperatures of -29°C (-20°F) or lower. Proper design and component selection result in luminaires that operate efficiently through these extremes.

Incandescent filament lamps operate at a very high temperature, near 2620°C (4750°F) for a 200-W lamp. Normal changes in ambient temperature do not appreciably affect its light output or life.

Ambient temperature and convection affect the performance of fluorescent lamps (see Chapter 6, Light Sources). In totally enclosed interior luminaires, fluorescent lamps

usually operate at temperatures above those for optimum light output. Ventilation and other means of heat dissipation are helpful and should be considered.

Ambient temperature normally is not a significant factor in the light output of conventional high-intensity discharge lamps. Starting requirements are sometimes affected at low temperatures, and ballasts meeting such requirements must be used. Special auxiliary equipment also may be required at elevated temperatures. The relationships between temperature and service life (wiring and components) must be considered. There are Underwriters Laboratories (UL), NEC, and Canadian Electrical Code (CEC)⁴ requirements that apply in some cases.

Radiation. Certain areas of buildings, especially laboratories with specialized equipment, may emit radiation that has a detrimental effect on the luminaire. These are special cases, and the possible effects of fading or color change of paints and degradation of plastics should be studied. In these cases, special consideration should be given to selection of luminaire materials.

Air Movement. Outdoor luminaires should be designed to withstand wind loading. In indoor locations, such as subway stations or small offices, the air pressure on a fluorescent troffer lens or a luminous ceiling component can dislodge a diffuser when doors are suddenly opened.

Miscellaneous Environmental Effects. A complete listing of the possible effects of the environment on luminaire design is impossible. The designer, however, should be alert to the possibilities of many others not specifically covered, such as the effect of UV energy on outdoor components, thermal shock, extremes in humidity, and foreign substances in the atmosphere.

Electrical Considerations. Sockets and lampholders, wire, ballasts, and other controls are parts of electrical circuits of luminaires. All gas discharge lamps require some form of ballast or control equipment to provide adequate starting voltage and to limit the current after the lamp has started.

Lamp Circuits. Each type of lamp requires a specific ballast circuit (see Chapter 6, Light Sources).

Ballast Quality. Rated lamp life and light output for fluorescent and HID lamps are directly dependent on the ballast's ability to meet specified limits set by the American National Standards Institute (ANSI) standards. Ballasts not meeting ANSI standards may reduce lamp life as much as 50% and light output by more than 30%.

The life of ballasts made with 105°C (Class A) insulation is approximately 45,000 h (continuous operation not exceeding 105°C). Ballast coil temperatures do not exceed the 105°C rating in properly designed ballasts when luminaires maintain a maximum ballast case temperature of 90°C. Other factors affecting ballast life are input voltage, luminaire heat dissipation characteristics, luminaire mounting, and the environment. Field data indicate a 12-yr median ballast life for a duty cycle of 16 h per day, 6 days per week, or 5000 h per year. This life rating assumes that because of bal-

last warmup time, the ballast operates only at peak temperatures for 12 h out of the 16-h duty cycle, or 3750 h per year.

Ballast safety standards are set by UL and CSA. Case temperatures of fluorescent lamp ballasts are limited to 90°C with the ballast mounted in a luminaire and the luminaire operating in an ambient temperature of 25°C. Ballasts for HID lamps have limits that apply to the coil and core temperatures, depending on the insulation system used; that is, whether it is rated for 105°C, 130°C, or 180°C.

Excessive ballast operating temperature causes ballast insulation deterioration, resulting in short life and possible activation of the ballast protective device. A convenient rule of thumb is that every 10°C increment above 90°C results in a 50% reduction in life. Luminaire design should limit heating within the luminaire.

Thermally Protected Ballasts. The NEC requires that thermally protected ballasts be used in some fluorescent and HID luminaires. For fluorescent lamp ballasts, UL requires that the protector open so that maximum ballast case temperature does not exceed 90°C when the luminaire is in service. Protected ballasts for fluorescent lamps are called Class P ballasts and are listed by UL as such. All new fluorescent lamp luminaires must use UL-listed Class P ballasts in order to carry the UL label. The intent is to limit the maximum temperature that a ballast case can reach in a luminaire under any condition. All recessed HID ballasts, both integral and remote, must be thermally protected.

High-Frequency Operation

Most fluorescent lamps can be operated on higher frequencies, resulting in increased luminous efficacy (see Chapter 6, Light Sources). As a rule, high-frequency ballasts are smaller, lighter, and more efficient.

Low-Temperature Operation. Fluorescent and HID lamps require higher open-circuit voltages for low-temperature starting. Low-temperature ballasts should be used where ambient temperatures are below 10°C.

Sockets and Lampholders. The ratings of voltage, current, and wattage should not be exceeded for any socket or lampholder. Limitations also usually exist for operations. Specific consideration should be given to the following:

- UL or Canadian Standards Association (CSA) listing and ratings should be followed for the specific application of any socket or lampholder.
- Materials used for contacts and screw shells, such as aluminum, copper, brass, nickel, stainless steel, silver, or plated metals and their alloys, limit the operating temperature, wattage, and current during use.
- Metallic, porcelain, plastic, or other nonmetallic housings have temperature limits that affect usage.
- Where high voltage or a starting pulse is required in lamp operation, the lampholder or socket, as well as associated wire, should be rated for these voltages or pulses.

- High temperatures occur with some lamps, such as tungsten halogen, and the wire, contacts, and housing should be rated for the temperatures that occur during lamp operation.
- Spring tension at lamp contacts may deteriorate under excessive temperatures or abuse, causing contact loss and deterioration and resulting in socket failure. Improper seating of lamps into a socket, as well as vibrations, can also cause arcing and contact deterioration. Arcing of lamp base pins, screw shells and other lamp or socket contacts can be detected through the burning or pitting of the material. Any lamps or sockets found with such deterioration should be replaced.
- Wet, damp, or hazardous environment applications, as well as usage in outdoors, mining, stage, or photographic locations, may require special consideration for sockets and lampholders.^{18,19}

Wire. The ratings of voltage and current should not be exceeded in the use of any wire. The material used for the conductor(s) and insulation may limit wire application, both indoors and outdoors. Specific considerations should be given to the local, state, and national electric codes designations for types of wire and their usage in various applications. Further limits are designated in UL and CSA standards for wire in specific luminaires. Common limitations include:

- Wire smaller than no. 18 American Wire Gauge (AWG) may not be used for line circuits of 120 V or higher.
- Luminaire wires have designations of 300, 600, or 1000 V, and higher-voltage wire may be required for some special applications.
- Wire temperature designations range from 60 to 200°C.
- Some applications require stranded wire, especially where it must flex.
- Nickel-plated conductors are common in high-temperature applications.
- Grounded cord sets are common.
- When luminaires are not wired through metallic conduit, a metallic luminaire should be grounded using acceptable ground wire.
- Users and specifiers should be familiar with electric codes, requirements for which include the use of at least no. 14 AWG wire for the supply leads of a recessed luminaire, despite a low-current requirement.

Starters and Igniters. Fluorescent, HID, and specialty arc lamps may be operated on circuits that include starters and igniters. They provide voltage pulses to start lamps, or a time delay to heat cathodes prior to lamp starting. They can also disconnect lamps from the circuit when the lamp fails. Accessibility is necessary for any that are replaceable or contain an element such as a spark gap that may fail and require replacement. Temperature limits must be observed for

starters and igniters, and they must be used only with the lamps and ballasts designated for them. The various circuits and lamp starter and igniter requirements are found in Chapter 6, Light Sources.

Mechanical Considerations

Tolerances. It is necessary to establish suitable dimensional tolerances for both the component parts and the final assembly. This includes allowances for the different rates of thermal expansion of the various parts. An industry standard²⁰ defines tolerances of recessed fluorescent lamp luminaires. Surface- and pendant-mounted luminaires may have less critical tolerances. When using recessed luminaires, availability of plenum space must be considered.

Strength. All luminaires should have housings of sufficient rigidity to withstand normal handling and installation. Local conditions, such as in earthquake areas, sometimes require conformity with special local codes.

Component Support. Lampholders and sockets should be fixed in place to prevent movement and to maintain good lamp contact in luminaires with double-ended fluorescent, tungsten-halogen, or HID lamps. To hold large, high-wattage incandescent and HID lamps, gripping sockets are often helpful. Large horizontally operated HID mogul base lamps benefit from the use of an end support. Ballasts should be securely fastened to the luminaire housing for good thermal contact. Door glasses, lenses, and refractors should be securely fastened to withstand the effects of wind, rain, and shock.

Mounting. Mounting components should satisfy the requirements of UL, CSA, local codes, and end-use environmental conditions. Tamper-proof fastenings may be required in public areas as well as in correctional institutions and mental hospitals. Wire guards may be required around exposed lamps in accessible locations. Local codes should be considered with regard to power supply, continuous row wiring, and grounding of the luminaire. Instructions and warnings should be marked in a readily discernible and permanent manner. The text and physical dimensions of instructions and warnings may be governed by code requirements.

Maintenance. Ease of maintenance is an important consideration. Instructions for maintenance and correct lamping should be provided to prevent luminaire damage and ensure performance. Electrical components should be replaceable without removing the luminaire from its mounting. Where ceiling plenums are not otherwise accessible, provision must be made for access through the luminaire to splice boxes that connect to the branch circuit.

Size. The size of a luminaire is usually controlled by components such as lamps, ballasts, and reflectors. Mounting limitations and building modules can also limit the size.

Thermal Considerations. The lamp efficacy, wattage, and type affect the temperature of a luminaire. Ballasts and transformers also affect the temperature, as does the lumi-

naire's environment. Finally, the heat-dissipating properties of the luminaire itself affect its temperature.

Very high or low ambient temperatures may cause electrical components to fail. For example, contact of hot glass with cold air or water may result in breakage, and excess heat may cause thermoplastics to distort. Satisfactory performance at the luminaire interior temperature is a major consideration in selecting components and finishes.

Higher-than-nominal line voltages usually cause higher temperatures within electrical components. Lower voltages do not necessarily produce lower temperatures.

Metal components and their finishes may be affected by temperature within a luminaire. Thought must also be given to metals as conductors of heat either to or from component parts.

Glass and plastic components should be chosen very carefully to prevent cracking, shattering, deformation, or other deterioration. This consideration may be long term, short term, or both.

Expansion or contraction of components due to thermal changes should be considered. Different coefficients of expansion between materials in close contact can lead to serious problems.

Safety Considerations. The need for attention to safety considerations, particularly in the design stage, cannot be overemphasized. Usually, if the design meets applicable code requirements, it conforms to the following criteria.

Electrical Safety. The safe conversion of electrical energy to light is of utmost importance. In this context important wiring considerations are:

- Current-carrying capacity of the conductors.
- Insulation rating of the conductors.
- Grounding. In most cases portable lighting equipment is required to have a polarized plug cap such that the screwshell of the socket is neutral or electrically dead. All permanently installed lighting equipment must be provided with grounding to eliminate shock hazard.
- Temperature rating of the conductors.
- Connections to the junction boxes. Where supplied, connections must be in conformance with local codes.
- Wire termination color coding in conformance with code requirements for safe field installation.
- Mechanical strength and flexing requirements.
- Safety interlocks. These are advisable in equipment where high open-circuit voltages are present for protection during servicing and are often advisable in damp areas and basements.
- Fuses and thermal protectors. Where required, these must be included in the design of the equipment.
- Applicable UL, CSA, and ANSI requirements for splices, clearances, and sockets.
- Low-voltage units. These should be considered for

outdoor applications and may be required around pools and hot tubs.

Thermal Safety. Luminaires should be designed to meet the requirements of the thermal environment and use. If the unit is to be firmly mounted and not handled during operation, it can operate at a higher temperature than a unit that must be held or moved by hand.

The NEC,³ the CEC,⁴ and their respective testing laboratories set specific temperature limits for electrical components and critical areas immediately surrounding a luminaire. Much of their testing is performed at an ambient temperature of 25°C (77°F). Code requirements usually do not relate to performance characteristics, and thermal considerations are regarded solely from a safety standpoint.

Ballasts and other auxiliary equipment, sockets, and wires have definite safe operating temperature limits defined by UL, CSA, ANSI, and the manufacturer. Special electrical components may have to be specified for extreme temperatures.

Ultraviolet Radiation. An enclosure and cover glass that absorb UV radiation may be required for some types of luminaires. Safety interlock switches are required to disconnect the lamps on opening the luminaire or on breakage of the glass cover. Labels should be provided with such luminaires to warn users of this hazard.

Many lamps produce some UV, but of insufficient quantities to require total enclosure and interlock switches. In applications such as museums, the long-term exposure to such UV radiation is considered a hazard (see Chapter 14, Lighting for Public Places and Institutions). Only UV-stabilized plastics do not transmit significant quantities of UV. Some food processing applications and UV-sensitive manufacturing processes require nearly complete elimination of UV. Common glasses transmit some UV and might not be appropriate in these applications.

Optical Design Methods

Luminaire optical design attempts to control and redirect the output of lamps to produce luminous output appropriate for an intended application. Optical design for luminaires is usually considered a type of nonimaging optics design, that is, the optics are intended to control the amount and distribution of emitted light for a desired photometric performance. This is different from imaging optics, where geometric rays of light are managed to preserve, manipulate, or modify images.

Overview of Reflector Design. The reflector design process produces a shape that reflects light from a lamp and generates a desired luminous intensity distribution. Reflector design almost always assumes the use of specular reflecting materials, though reflector analysis can account for real (nonspecular) reflectance of materials. The process is as follows.

1. Choose the lamp appropriate for the application. Consider the luminaire mounting and size and other requirements such as thermal conditions, need for sealing, and lamp access.
2. Evaluate the nominal luminaire output and determine the luminous intensity distribution or the illuminance distribution on the target plane. In many applications, flux is contributed to the luminous intensity distribution or arrives at the target plane direct from the lamp. The difference between the nominal distribution and that provided by the lamp is what the reflector must provide.
3. Determine other factors that affect distribution, such as cutoff, shielding, and the behavior of lamp images in the reflector.
4. Optionally, scale the nominal lumen output of the luminaire so that it is consistent with the lumens available from the lamp, the reflectance of the material being used, and the number of interreflections the light undergoes before it leaves the luminaire.
5. Generate a reflector shape using either of two general procedures: flux mapping and flashed area. For flux mapping, reflector shape is determined either from a closed mathematical solution to the problem or iteratively by successively closer approximations. The simplest of these procedures assumes a point source.²¹ More elaborate techniques have been devised to account for lamp size.²²⁻²⁴ The flashed area procedure usually results in a faceted reflector. Individual facets are designed to send flux into particular directions, taking into account the size and luminance of the lamp.
6. Construct and prototype and test for photometric performance.

Theoretical shapes offer some guidance regarding lamp and reflector behavior. In the simplest case, the lamp is a point source and the reflector is perfectly specular. A few of the conic sections are useful.

Parabolic Reflectors. An inherent property of the parabola is its ability to redirect a ray of light originating at its focal point along a direction parallel to the axis of the parabola. If the parabola is rotated about its axis, a paraboloid is swept out. Assume a perfectly specular mirror is made to this shape, and that a point source is at the focus. Then all light from the source striking the mirror is redirected as a circular beam parallel to the parabolic axis. Similarly, the parabola can be extruded and placed around a line source, producing a rectangular beam.

The larger the lamp is, the greater the deviation of the light from a parallel beam. Formulas have been derived expressing the light divergence from shallow mirrors when sources of various shapes are used.

Ellipsoidal Reflectors. If an ellipse is rotated about its major axis, a surface is swept out which is an ellipsoid. This

surface, having two foci, takes light from one focus and reflect it through the other focus. Ellipsoidal reflectors are an efficient means for producing beams of controlled divergence and for collecting light to be controlled by a lens or lens system. This shape can also be extruded.

Spherical Reflectors. A spherical reflector can be considered as a special form of the ellipsoidal reflector where the two foci are coincident. Any light leaving the source located at the focus returns and passes through the same point. This can cause problems when using some HID sources, since the concentration of energy can damage the source or the bulb wall surrounding it. However, the principle is often used in projecting devices to increase the amount of light collected by a lens, and in the design of reflectors for fluorescent lamps.

Implementation of Reflector Design. The simplest case of flux mapping reflector design involves the following assumptions:

- The source is axially symmetric and sufficiently smaller than the reflector so that it can be considered a point source.
- The nominal luminous intensity distribution is axially symmetric.
- The material used for the reflector exhibits very specular reflectance.

The procedure begins by determining the difference between the flux provided directly by the source (see Figure 7-54b) and the flux required to give the nominal luminous intensity distribution. The reflector is generated incrementally by determining the shape necessary to reflect light from the source and make up this difference. The steps are as follows:

1. The point source is located at the origin of a spherical coordinate system shown in Figure 7-54a. Angles describing intensities or flux from the source are measured from zenith. Angles describing intensities or flux into the luminaire distribution are measured from nadir.
2. Determine the angular size of the opening at the back of the reflector, α_o , and the initial distance, r_o , from the source to the reflector at this angle. These are usually fixed by lamp size, desired reflector size, the need for mounting, and lamp socket placement.
3. Determine the available luminous intensity distribution, $I_s(\alpha)$ of the source. This is available from lamp manufacturers and often is provided as axially averaged values if the lamp is nominally axially symmetric.
4. Determine the nominal luminous intensity distribution, $I'(\beta)$, of the luminaire, including the cut-off angle, Θ . Usually the relative shape of $I'(\beta)$ (the indicatrix) is constrained by some requirement, whereas the magnitude is not. A specific illuminance distribution requirement, such as a limit on the ratio of maximum to minimum illuminance, is an example of such a shape constraint. Requirements of cut-off angle for computer area lighting applications is another.
5. Calculate the available (source) flux distribution of the source, $\Phi_s(\alpha)$, using the source luminous intensities and the solid angle of annular cones in α .
6. Calculate the nominal flux distribution, $\Phi'(\alpha)$, using the nominal luminous intensities and the solid angles of annular cones in β .
7. Calculate the flux in the nominal intensity distribution, the total flux emitted by the source, the flux provided by the source directly into the distribution, and the flux provided by the source after redirection by the reflector. Note that the cut-off angle, Θ , may not fall on a cone boundary. If the angular increment that defines the cones is small, the error introduced is small.
8. Calculate the scale factor K for achieving flux balance by accounting for the flux available from the lamp and the reflectance ρ . If $K < 1.0$ then the source and reflector cannot meet the flux requirements of the nominal distribution and either the reflector must be scaled down or the source output increased. If $K > 1.0$ then source and reflector should produce more flux than required and the nominal distribution is scaled up or the source output decreased.
9. Calculate the actual luminaire intensity distribution, $I(\beta)$, and the flux distribution, $\Phi(\beta)$, by scaling with K . In other words, $I(\beta) = I'(\beta) K$ and $\Phi(\beta) = \Phi'(\beta) K$.
10. Determine the required (reflected) flux distribution, $\Phi_r(\beta)$, by subtracting the direct (source) flux from the luminaire flux, or $\Phi_r(\beta) = \Phi(\beta) - \Phi_s(\pi - \beta)$. $\Phi_r(\beta)$ is the flux that the reflector must provide to produce the final distribution of the luminaire. It is assumed that this flux comes from the source by only one reflection of the reflector. Note that source angles are specified from zenith, so $\pi - \beta$ is used.
11. Calculate the cumulative available flux function $\Sigma\Phi_s(\alpha)$ and cumulative required flux function $\Sigma\Phi_r(\beta)$. Figure 7-55 shows examples of these cumulative functions. The use of K guarantees that the final (maximum) value of $\Sigma\Phi_s(\alpha)$ equals that of $\Sigma\Phi_r(\beta)$. The appropriate reflector shape distributes the available flux according to the required flux distribution. That is, any fraction of available flux must be matched by the same fraction of required flux. Thus, a relationship is established between β and α by matching flux fractions.

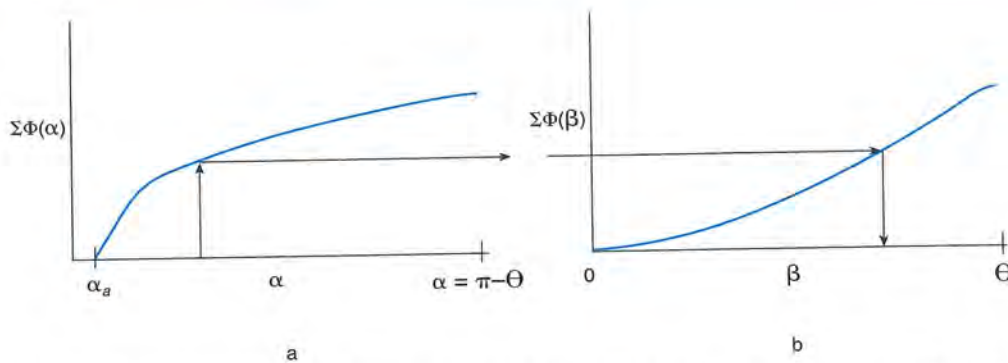


Figure 7-55. (a) Cumulative available flux distribution of the source, and (b) cumulative required flux distribution of the reflector.

12. Using $\Sigma\Phi_s(\alpha)$ and $\Sigma\Phi_r(\beta)$, determine pairs of (α, β) . Figure 7-55 shows this procedure graphically. For each α , use the $\Sigma\Phi_s(\alpha)$ function to determine a fraction of available flux. At this same fraction, use the $\Sigma\Phi_r(\beta)$ function to determine the matching β .
13. For each pair of angles (α, β) , calculate the angle ϵ that the reflector must have at that α to send flux in the direction β (see Figure 7-56a.)
14. Beginning with α_o , r_o , and ϵ_o , use the sequence of values α_i and ϵ_i to calculate the radial distances r_i from the source to the reflector and thus the coordinates (x_i, y_i) of the reflector (see Figure 7-56b). The step size in α determines the size of the reflector facets. A smooth interpolating curve can be passed through the point (x_i, y_i) .

In the procedure outline above, the (α, β) pairs are generated so that a small value of β (perhaps zero) is matched with α_o . There are simple modifications to this procedure that gener-

ate other reflector shapes using the same source and nominal luminous intensity. The cumulative available flux distribution can be reversed so that it begins with $\alpha = \pi - \Theta$, and this is matched with a small value of β . Additionally, for each of these two cases, the reflector slope ϵ can be changed so that flux does not cross the axis of the luminaire. Thus, there are four possibilities, as shown in Figure 7-57. The procedure given here generates the smallest reflector. Similar procedures can be used to generate a shape for an extruded reflector using a source that is assumed to be a line.

Overview of Refractor Design.^{25,26} Luminaire refractor design is typically used to produce prismatic lenses. With the exception of some special applications such as automotive headlights, refractors are designed using a procedure similar to that for reflectors. In addition to luminous intensity distribution requirements, refractors can be designed to hide lamps or otherwise to spread emitted flux over the full extent of the prismatic lens. This produces a luminaire luminance that can be significantly less than that of the lamp.

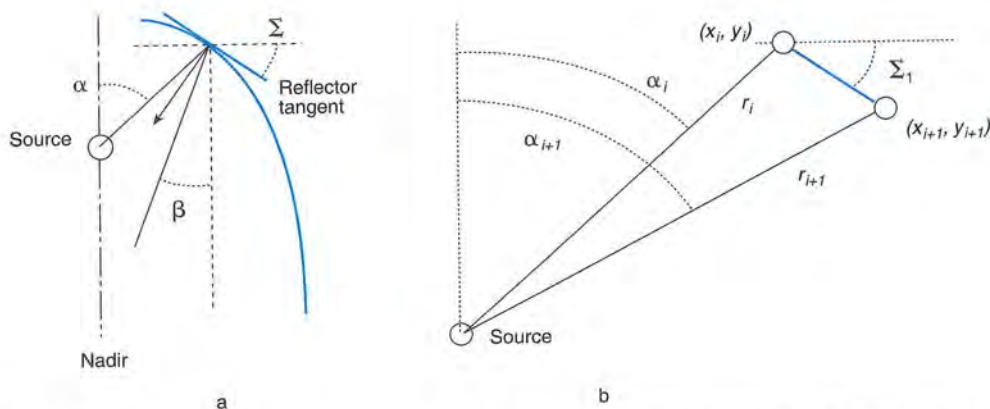


Figure 7-56. (a) Local tangent of reflector for angle pair (α, β) , and (b) determination of reflector coordinates.

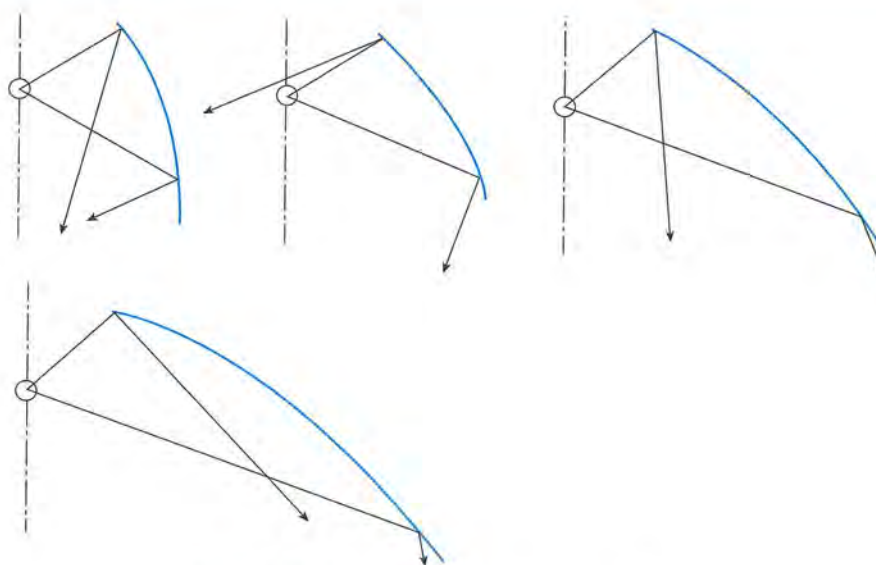


Figure 7-57. Four basic reflector shapes for point sources.

The basics of refraction are addressed in Chapter 1, Light and Optics.

Individual prisms are designed to refract light into appropriate directions, or in some cases to provide for total internal reflection. Prism size and angles are affected by the index of refraction of the material. Geometric ray tracing is almost always used to determine the size and angle of the optic surfaces.

Prototyping refractors is more difficult than for reflectors. Machining is used to produce temporary molds for plastic refractors. In other cases, optical material is machined directly and suitably finished to produce a prototype refractor.

Computer Modeling^{27,28}

Analysis. Modern computer technology has produced powerful photometric analysis tools to evaluate proposed luminaire optical designs. In most cases, photometric ray tracing is used to model the interaction of light and the reflector surface. Reflectance models are available to describe the directional reflectance characteristics of real reflector surface finishes. These computer simulation tools can also model the effects of refractors. The reflector and/or refractor shapes are described in one of the standard forms for CAD drawings. Lamp and material characteristics are specified from a library of available data.

Synthesis. Reflector shapes can be synthesized in certain situations. These procedures involve elaborate iterative procedures, such as “genetic algorithms”²⁹ that systematically modify and evaluate a reflector shape. Closed procedures have also been developed to account for lamp size and produce a reflector shape that generates the nominal luminous intensity distribution. These procedures are currently limited to axially symmetric or extruded reflectors.

Prototypes. Prototypes of luminaires are made to test optical designs, that is, to identify problems in the photometric performance of the luminaire and help determine manufacturing issues for the luminaire. Simple handmade prototypes of metal, plastic, cardboard, and other temporary framework are constructed to hold reflective film. Parts can be machined in metal or plastic according to design specifications and then polished or coated to give an adequate approximation of the final shape and specular finish.

Computer-driven laser and resin tomography can produce prototype shapes of cured resin, which are then polished and coated to make a reflector. In this process, the reflector design is expressed in instructions for a machine that guides intersecting laser beams passing through a vat of liquid resin. Where the beams overlap the resin solidifies. Complex three-dimensional shapes can be generated quickly and inexpensively.

CONSTRUCTION OF LUMINAIRES

Materials Used in Luminaires

The materials most commonly used in luminaires are glass, plastics, metals, and applied finishes and coatings. Each of these materials is briefly described below. For more specific applications the material manufacturer’s data should always be consulted.

Glass. Glass is an inorganic product of fusion that has been cooled to a rigid condition without crystallizing. Chemically, glasses are mixtures of oxides such as silicon, boron, aluminum, lead, sodium, magnesium, calcium, and potassium. The chemical and physical properties of glasses, such as color, refractive index, thermal expansion, hardness, corrosion resistance, dielectric strength, and elasticity, are ob-

tained by varying the composition, heat treatment, and surface finish. Glasses used in luminaires can be classified into several groups with characteristic properties.

Soda-Lime. Soda-lime glasses (or lime glasses) used for windows, incandescent lamp bulbs, lens covers, and cover glasses (tempered) are easily formed when heated and are usually specified for service where high heat resistance and chemical stability are not required.

Lead-Alkali. Lead-alkali glasses (or lead glasses) are used for fluorescent and HID lamp bulbs, neon sign tubing, and certain optical components. They are useful because they are easy to form and have high electrical resistivity and high refractive indices. When formed, however, they do not withstand high temperatures or sudden temperature changes. UV radiation is absorbed by this type of glass.

Borosilicate. Borosilicate glasses are used for refractors, reflectors, and sealed beam lamp parts because of their high chemical stability, high heat shock resistance, and excellent electrical resistivity. They may be used at higher temperatures (about 230°C) than soda-lime or lead-alkali glasses, but they are not as convenient to fabricate. Near UV radiation is transmitted by this glass.

Aluminosilicate. Aluminosilicate glasses are used where high thermal shock resistance is required. They have good chemical stability, high electrical resistivity, and a high softening temperature, enabling use at moderately high temperatures (about 400°C).

Ninety-Six-Percent Silica. Ninety-six-percent silica glasses are used where high operating temperatures are required. They may be regularly used at 800°C. They are also useful because of their extremely high chemical stability, good transmittance to UV and IR radiation, and resistance to severe thermal shock. They are considerably more expensive than soda-lime and borosilicates and are more difficult to fabricate. Because of their low coefficient of thermal expansion, these glasses cannot be tempered to increase mechanical strength.

Vitreous Silica. Vitreous silica is a glass composed essentially of SiO_2 . It is used for lamp bulbs and arc tubes where high-temperature operation and excellent chemical stability are required. It has high resistance to severe thermal shock; high transmission to UV, visible, and IR radiation; and excellent electrical properties. However, due to its low coefficient of thermal expansion, it cannot be tempered to increase mechanical strength. Depending on the method of manufacture, this glass may be known as fused silica, synthetic fused silica, or fused quartz.

Functions. The functions of glass in lighting may be divided into the following general categories: (1) control of light and other radiant energy, (2) protection of the light source, (3) safety, and (4) decoration. These functions may be combined for a particular application. Typical properties of glasses are shown in Figure 7-58.

Plastics.³⁰ Plastics generally are high-molecular-weight organic compounds that can be, or have been, changed by ap-

plication of heat and pressure, or by pressure alone. Once formed, they retain their shape under normal conditions.

Plastics can be broadly classified as thermoplastic or thermosetting. Thermoplastic resins may be repeatedly softened and hardened by heating and cooling. No chemical change takes place during such actions. Thermosetting resins cannot be softened and reshaped once they have been heated and set, since their chemical structure has changed. Some of the commercially important thermoplastics are acrylonitrile butadiene styrenes (ABS), acrylics, cellulose, acetals, fluorocarbons, nylons, polyethylenes, polycarbonates, polypropylenes, polystyrenes, and vinyls. In the thermosetting group, resins of importance are epoxies, melamines, phenolics, polyesters, ureas, and silicones.

Most resins, whether thermoplastic or thermosetting, can be processed into structural or low-ratio expanded foams. Among the important properties of many foams are stress-free parts, improved insulation characteristics and lighter weight, and sometimes greater strength and toughness than the unfoamed form of the material. Important resins and properties of plastics used in lighting are shown in Figures 7-59 and 7-60, respectively.

Fillers and reinforcing agents frequently are added to plastics to obtain improved heat resistance, strength, toughness, electrical properties, and chemical resistance, and to alter formability characteristics. Some of the fillers and reinforcements in general use are aluminum powder, asbestos, calcium carbonate, clay, cotton fibers, fibrous glass, graphite, nylon, powdered metals, and wood flour.

The basic compounds from which today's plastics are produced are obtained from such sources as air, water, natural gas, petroleum, coal and salt, biomass, and wood fiber. The required chemicals are reacted in large closed vessels under controlled heat and pressure with the aid of catalysts. The resultant solid product is then subjected to such further operations as reduction of particle size; addition of fillers, softeners, and modifiers; and conversion of form to granules, pellets, and film.

If the plastic surfaces need protection from UV radiation, an UV-resistant film can be laminated onto the surface facing the energy source. UV-resistant clear coatings can also be applied on the interior and exterior surfaces of transparent plastic materials to retard discoloration. Optically transparent plastics may have UV stabilizer introduced into the base resin of the material for maximum UV resistance.

Steel. In the fabrication of lighting equipment, steel serves primarily in a structural capacity. Sheet steel, while having the great strength and low cost needed for a large-volume material, must be processed additionally with platings or applied coatings before it can serve as a light-controlling medium. Many grades and types of sheet steel are available in a variety of forms.

Sheet steel used in lighting equipment is of three basic types: hot-rolled steel, cold-rolled steel, and porcelain enameling sheets. Hot-rolled steel, because of the rolling

Figure 7-58. Properties of Glasses Used in Luminaires

Type of Glass	Color ^a	Coefficient of Thermal Expansion per °C ^b ($\times 10^{-7}$)	Upper Working Temperatures °C(°F) (Mechanical Considerations Only)				Thermal Shock ^{e,f} Resistance Plates 15 cm $\times$ 15 cm $\times$ 0.64 cm (6 in. $\times$ 6 in. $\times$ 1/4 in.) thick	Impact Abrasion Resistance ^g	Density (grams per cc)	Young's Modulus		Poisson's Ratio ^h	Refractive Index (589.3 nm)
			Annealed		Tempered					(10 ⁶ kg/cm ²)	(10 ⁶ lb/in ²)		
			Normal Service ^{c,e}	Extreme Limit ^{d,e}	Normal Service ^{c,e}	Extreme Limit ^{d,e}							
Soda-Lime	Clear	85–97	110 (230)	430–460 (806–860)	200–240 (392–464)	250 (482)	50	1.0–1.2	2.47–2.49	0.7–0.71	10–10.2	0.24	1.512–1.514
Lead-Alkali	Clear	85–91	110 (230)	370–400 (698–752)	220 (428)	240 (464)	45	0.56	2.85–3.05	0.61–0.62	8.7–8.9	0.22	1.534–1.56
Borosilicate	Clear	32–46	230 (446)	460–490 (860–914)	250–260 (482–500)	250–290 (482–554)	100–150	3.1–3.2	2.13–2.43	0.65–0.66	9.3–9.5	0.20	1.474–1.488
Aluminosilicate	Clear	34–52	200 (392)	650 (1202)	400 (752)	450 (842)	100–150	2.0	2.43–2.64	0.87–0.89	12.5–12.7	0.25	1.524–1.547
96% Silica	Clear	8	800–900 (1472–1652)	1090–1200 (1994–2192)			1000	3.5–3.53	2.18	0.67	9.6	0.18	1.458
Vitreous Silica	Clear	5.5	1000 (1832)	1200 (2192)			1000	3.6	2.2	0.73	10.4	0.16	1.458

^a All glasses can be colored by the addition of metallic oxides that become suspended or dissolved in the parent glass, usually without substantially changing its chemical composition or physical properties.

^b From 0° to 300°C, in./in./°C, or cm/cm/°C.

^c Normal service: no breakage from excessive thermal shock is assumed.

^d Extreme limits: depends on the atmosphere in which the material operates. Glass will be very vulnerable to thermal shock; tests should be made before adopting final designs.

^e These data approximate only.

^f Based on plunging sample into cold water after oven heating. Resistance of 100°C means no breakage if heated to 110°C and plunged into water at 10°C. Tempered samples have over twice the resistance of annealed glass.

^g Data show relative resistance to sandblasting.

^h Value applies to only one glass of group.

Figure 7-59. Uses of Resins in Lighting Applications

Resin	Uses
Thermoplastics	
Acrylics	louvers, formed light diffusers, prismatic lenses, diffusers, film
Cellulosics	sign faces, vacuum-formed diffusers, globes, light shades, light supports
Flexible vinyls	gaskets, wire coating
Nylons	electro-mechanical parts, wire insulation, coil forms
Polycarbonates	insulators, globes, diffusers, antivandalism street lighting globes
Polyethylenes	(high density)—wire coatings, housings
Polyethylenes	(low density)—formed light diffusers, blow-molded globes
Polystyrenes	same as acrylic
Rigid vinyls	formed lighting diffusers, corrugated sheet for luminous ceilings
Thermosetting	
Melamines	switches, insulators
Phenolics	wire connectors, switches, sockets, shades
Polyesters	(glass reinforcing)—shades, reflector housings, diffusers
Ureas	louvers, lampholders, shades
Filled reinforced plastics	insulators, reflectors, housings, globes, light shades, switch bases

process at elevated temperatures, carries an oxide coating (mill scale). It is not normally used where a smooth appearance is desired. The scale can be removed in an acid bath (pickling), but the surface is still somewhat rough. Cold-rolled steel is used primarily because of its smooth surface appearance. It is also available in thinner gauges than hot-rolled steel. It is usually obtained by pickling hot-rolled steel coil and further reducing the thickness without heating. Porcelain enameling sheets have very low carbon content in order to prevent mill scale beneath the porcelain coating. All of these steels are available in several grades and finishes. The types of finishes include galvanized sheet, prepainted sheet, aluminum-clad sheet, and plastic-coated sheet. Pre-plated sheets are also available, and the platings include chrome, brass, and copper.

Steel sheet used in lighting is often referred to by its thickness, or gauge. The metal gauge most commonly used is the Manufacturer's Standard Gauge for Steel Sheets.

Aluminum. Aluminum is a nonferrous, corrosion-resistant, lightweight, nonmagnetic metal having good thermal and electrical conductivity. It is high in the electrochemical series but resists attack by either air or water because of the formation of an invisible protective covering of aluminum oxide.

Uses in Lighting. Aluminum is used in lighting for structural parts such as tubes or poles, housings, channels, mechanical parts, and trim, and for light-controlling surfaces such as reflectors, louvers, and decorative surfaces. Aluminum is also used as a reflecting surface when vaporized

on glass and plastic, and as a paint when in fine powder form and suspended in a suitable liquid vehicle. An aluminum reflector can have a high-permanence, high-reflectance, diffuse, or semidiffuse surface of graduated reflectance.

Types of Aluminum. Aluminum is used in its near-pure state or may be alloyed by the addition of other elements to improve its mechanical, physical, and chemical properties. Silicon, iron, copper, manganese, magnesium, chromium, nickel, and zinc are the most common elements used. Aluminum alloys may be cast, extruded, and rolled as shapes or sheets. In sheet form, aluminum is available in a variety of alloys and finishes.

Finishes. The final finish on aluminum parts depends on service requirements. Aluminum may be etched, polished, brushed, plated, anodized, vacuum coated with a dielectric, color anodized, brightened, plastic coated with or without vaporization, coated with clear or dye lacquers, finished with baked or porcelain enamel, or given some combination of these finishes. Reflector finishes may range from diffuse, such as baked enamel or etched surfaces, to highly specular, such as polished, anodized, or coated surfaces. Aluminum paint has found wide use as an attractive and practical finish for many surfaces.

Processing. Anodizing, an electrochemical process, is used to form a protective surface of aluminum oxide of a thickness greater than 100 times that formed naturally in air. The aluminum oxide surface is smooth, continuous, and inseparable, with a particle hardness of Mohs value 9. Anodizing combined with chemical or electrochemical brightening provides surface finishes of uniformly high reflectance and permanence.

High-purity aluminum must be used if a clear, colorless transparent, high-reflectance oxide surface is required. Impurities and alloying materials result in lower reflectance, cloudiness, dullness, or streaking of the oxide surface. Pre-finished anodized sheet is available for forming simple reflector elements. Figure 7-61 gives typical reflective properties of various types of aluminum.

In the anodizing process, colored surfaces may be obtained by depositing dyes or pigments within the open pores of the aluminum oxide just before the final sealing of the surface. A wide range of colors and tints are available.

Physical Characteristics. Properties of several alloys of aluminum that may be of interest to the designer are shown in Figure 7-62. The types and values shown are intended as typical illustrations. New alloys are being developed continually, and any contemporary listing rapidly becomes out of date.

Other Metals

Stainless Steel. Stainless steel includes those iron-base alloys that contain sufficient chromium to render them corrosion resistant. The classification "stainless" is usually reserved for those steels having 12 to 30% chromium; those with more than 30% are classed as heat-resisting alloys and not as stainless. The family of stainless steels may be di-

Figure 7-60. Properties of Plastics Used in Luminaires

Materials	Common Forms										Reasons for Use and General Data										Secondary Methods																
	Castings	Compression Moldings	Extrusions	Fiber	Film	Foam	Injection Moldings	Rotational Molding	Sheet	Reinforced Plastic Moldings	Industrial Laminates	Chemical Resistance	Colorability	Flammability Rating*	Flexibility	High Dielectrics	Low Moisture Absorption	Clarity	Strength and Rigidity	Toughness	Effect of Ultraviolet†	Resistance to Heat °C	Resistance to Impact	Metalizable	Plating	Dichroic Coating	Hard Coating	Paint	Hot Stamp Inks/Foils	Pad Printing	Sonic Weld	Sonic Staking					
THERMOPLASTICS																																					
ABS	X		X				X		X			X	X	HB-VO		X				X	X	NP	60-110		X												
Acetals													X	HB		X				X	X	C	80														
Acrylics									X					HB		X				X	X	N	60-90														
Acrylics (High Heat)																					SL	95-110															
Acrylic-Styrene																																					
Copolymers													X	HB-VO		X	X			X	X	NP-SL	80-95														
Cellulose Acetates																					SL	65-105															
Cellulose Acetate													X	HB		X				X	N	60-105															
Butyrate													X	VO		X				X	CO	260															
TFE-Fluorocarbons														HB-VO		X				X	SL	80-150															
Nyons														HB-VO		X				X			120														
Polycarbonates																							180-200														
Polyesters														HB-VO		X				X			120-160														
Polyetherimides																							80-120														
Polyethylenes																							180-200														
Polyethylene Oxide																							120-160														
Polypropylenes														HB-VO		X				X	NP	80-110															
Polystyrenes														HB-VO		X				X	NP	120-160															
Polyphenylene Sulfides														HB-VO		X				X	NP	75-95															
Polyisulfones														V1-VO		X				X		200-250															
Styrene Acrylonitrile														HB-VO		X				X	NP	150-175															
Copolymers														HB-VO		X				X	SL	80-95															
Vinyls														HB-VO		X				X		65-95															
THERMOSETTING PLASTICS																																					
Epoxies	X													HB-VO		X				X	SL	120-290															
Melamines		X												VO		X				X	SL	100															
Phenolics														HB-VO		X				X	D	120															
Polyesters														HB-VO		X				X	SL	150-210															
Polyesters (Molding Compounds)														HB-VO		X																					
Silicones														HB-VO		X					SL	150-175															
Ureas														HB-VO		X					SL-N	315															
														V1-VO		X					G	75															

* See Reference 31.

†NP-needs protection, C-chalks, N-none, SL-slight, CO-colors, D-darkens, G-grays.

Figure 7-61. Typical Reflective Properties of Aluminum

Aluminum Purity	Designation	Reflectance, specular sheet with 0.2 mil anodic coating	Reflectance, diffuse sheet with 0.2 mil anodic coating
99.99%	Lurium	0.90	0.85
99.90%	3002	0.82	0.78
99.80%	1100 or 5005	0.76	0.72
		0.73 with 0.4 mil coating	0.70 with 0.4 mil coating
99.70%	3003	0.68	0.65

vided into three main groups: straight chrome, chrome-nickel, and chrome-nickel-manganese. Straight chrome steels are all magnetic. They may rust on exposure to corrosive atmospheres; however, the rusting is only a superficial film and acts as a barrier to further corrosive action. These are identified by the American Iron and Steel Institute (AISI) as AISI Type 400 Series. Chrome-nickel steels are nonmagnetic. They do not rust, but some alloys may not be satisfactory in certain corrosive atmospheres. These steels are designated as AISI Type 300 Series. Chrome-nickel-manganese steels are nonmagnetic. In this group, manganese substitutes for part of the nickel. These steels do not rust, but some alloys may not be satisfactory in certain corrosive atmospheres. These steels are designated as AISI Type 200 Series.

Stainless steels are widely used in luminaires intended for outdoor installation or in other corrosive atmospheres. Some applications of stainless steel are for housings, springs, latches, mounting straps, hinges, fittings, fasteners, and lampholder screw shells.

Copper. Copper is used extensively for the conductors, bus bars, and associated switchgear necessary for the distribution and control of electrical energy used for lighting. Copper is ductile, malleable, flexible, and fairly strong and

may be formed by a variety of standard machines and processes.

Nonferrous Alloys. Bronze, an alloy of copper and tin, and brass, an alloy of copper and zinc, are often used in special luminaires where the attractive color is a prime consideration. A more utilitarian use of bronze and brass is in luminaires for marine use, where strength and resistance to saltwater corrosion are highly important. Chromium copper and beryllium copper are often used for conducting springs, contacts, and similar highly stressed members that have to be formed in manufacture. The parts are shaped soft and then stiffened by heat treatment.

Fiber Optic. Polymethacrylate (PMMA) and various copolymer products are the most widely used plastic materials for the manufacture of plastic optical fiber. PMMA fibers (SPF) are small diameter fibers on the order of 125 to 3000 μm . The copolymer products (LPF) are available with diameters of 3 to 19 mm.

Plastic optical fiber (POF) is sensitive to ultraviolet wavelengths, high temperature, and the radiant power density of light incident on its ends. POF absorbs radiation in the ultraviolet spectrum. Over time, plastic fiber yellows and becomes unusable if subjected to unacceptable

Figure 7-62. Typical Physical Properties of Aluminum

Type	Alloy	Federal Specification Number	Average Coefficient of Thermal Expansion*	Specific Gravity**	Thermal Conductivity at 25°C (CGS units)	Reflectance (percent)
Specular, processed sheet	#12 Reflector sheet	($\mu\text{cm/cm}$)	23.6	2.71	0.53	80-95
Diffuse, processed sheet	#31 Reflector sheet		23.6	2.71	0.53	75-80
Mill finish sheet	#1100-H14	QQ-A-561c	23.6	2.71	0.53	70
Extruded	#6061-T4	QQ-A-270a	23.4	2.7	0.37	
Extruded	#6063-T4	QQ-A-274	23.4	2.7	0.46	
Extruded	#6463-T4		23.4	2.7	0.52	
Cast, sand, or permanent	#43-F	QQ-A-371c	22.1	2.69	0.34	
Cast, sand, or permanent	#214-F	QQ-A-371c	22.3	2.89	0.29	
Cast, sand (heat treat)	#220-T4	QQ-A-371c	24.7	2.57	0.29	
Cast, die	#360	QQ-A-591a-2	20.9	2.64	0.27	
Cast, die	#380	QQ-A-591a-2	20.9	2.72	0.23	

* °C, 20 to 100°C.

** Also weight in g/cm^3 .

amounts of ultraviolet radiation. Like most plastics, POF melts or burns if subjected to high levels of infrared radiation or heat. In addition, if too much light is put into the fiber, the fiber rapidly burns or darkens. For example, some POF is rated at a maximum luminous power capacity of 30 lm/mm². Power densities below this value ensure a long operating life.

SPF has an acceptance angle of 66°. The various LPF products have acceptance angles between 75 and 80°.

Glass Fiber. Glass optical fibers are typically 50 to 150 μ m in diameter. Glass can be manufactured in larger diameters, but its lack of flexibility quickly precludes its use in practical architectural applications. The small individual glass fibers are grouped together in bundles (GFB) of various diameters. These bundles of extremely small fibers result in light guides that are very flexible. Glass fiber has a greater radiant power handling capacity and longer life and can operate continuously at higher temperatures than POF. These characteristics make GFB useful where harsh environmental requirements prevent the use of POF.

Glass fiber is impervious to the ultraviolet spectrum. Designers need not concern themselves with fiber degradation resulting from UV radiation, but they should be aware that although most GFB available for lighting applications absorbs and thus filters UV radiation, some glass fiber is designed to transmit specific UV wavelengths.

The numerical aperture (NA) of glass fiber can vary with the index of refraction of the component materials. Typically the numerical apertures of glass fibers are 0.64 and 0.55, yielding acceptance angles of 80° and 66°, respectively.

The ends of glass fibers must be terminated and polished by the manufacturer. Users generally must specify the required lengths of an application when placing an order. In contrast, POF can be cut to any desired length in the field at the time of installation.

Finishes Used in Luminaires

A finish is the final treatment given to the surface of a material in the course of manufacturing to render it ready for use. Three major purposes for finishes on lighting equipment are the control of light, the protection of material, and the enhancement of appearance. In addition, there are finishes for several special applications, such as flame-retardant and color-stabilizing treatments.

Finishes are classified both by the method of application and by the kind of material applied. The three basic types are coatings, laminates, and chemical conversion finishes. Coatings can be divided into four general classes: organic, ceramic, metallic, and other.

Typical characteristics of finishes are indicated in Figure 7-63. Because of the great number of possible variations in composition and application of all types of finishes, numerical values are not shown and relative gradings only are used. For more details on finishes, technical assistance should be obtained from suppliers and available literature.

Coatings

Organic Coatings. Lacquers are clear, transparent, or opaque and cure rapidly at room temperature. They may be used for decoration or protection. Enamels are pigmented coatings and are applied for protection, decoration, or reflectance. They cure by oxidation (air or forced drying) or polymerization (baking or catalytic action) and result in tougher finishes than lacquers. Baked clear coatings, sometimes called baking lacquers, are used for decoration and protection. They cure by polymerization (baking or catalytic action).

Organisols and plastisols are usually applied by dipping and spraying. These plastic dispersion coatings offer good exterior corrosion as well as scratch and abrasion resistance and also are able to conceal many surface defects.

Ceramic Coatings. Ceramic coatings, including porcelain enamels, are fired on glass and metals at temperatures above 540°C. Primary features on metals include high resistance to corrosion, good reflectance, and easy maintenance, and on glass, reduction of brightness and increase of diffusion.

Metallic Coatings. Electrochemical deposition, commonly called electroplating, causes a second metal to be deposited over the first by means of an electrolytic action. Zinc, cadmium, or nickel is used to provide protection. Brass and silver finishes are primarily decorative.

Vacuum metallizing consists of vaporizing a metal, usually aluminum, in a vacuum chamber and depositing it on surfaces of plastic, glass, or metal. Finishes of high specular reflectance are obtained and can be used for either light control or decorative purposes. Dip and spray coatings, as in galvanizing, are deposits of a second metal to protect the base metal against corrosion.

Other Coatings. Semiconductors, such as silicon and germanium, and inorganic dielectrics, such as magnesium fluoride and titanium dioxide, are vacuum deposited on such materials as glass, aluminum, and plastics. The coatings of interest for lighting uses are multilayered and less than 1 μ m thick.

Laminates. This type of finish is created by bonding a thin layer to a base material, such as a plastic film to sheet metal. The laminate can be a decorative material or it can be a light-controlling material.

Chemical Conversion Finishes. Anodizing converts an aluminum surface by an anodic process to aluminum oxide, which has outstanding protective qualities against corrosion and abrasion. The resultant finish may be clear or can be dyed in a variety of colors.

Overview of Manufacturing Methods

Metal Working

Spinning. In this process a metal blank in the form of a thin disk is mounted against a wood or steel chuck between the headstock and the tailstock of a lathe. While the blank

Figure 7-63. Properties of Finishes Used in Luminaires

Type of Finish	Method of Application*	Principal Uses ^b	Colors Possible	Character of Reflected Light	Percent Reflectance ^c	Resistance ^d			Flammability		
						Heat	Corrosion	Abra-sion	Im-pact	Sta-bility ^e	
Organic coatings											
Lacquers	D, B, S	A, P	Colorless or any color	Mixed to diffuse	10-90	F	F	P	F	F	Slow burn
Emulsions	D, B, S	A, P	All colors	Mixed to diffuse	10-90	G	G	G	G	G	Slow burn
Enamels	D, B, S	A, P, R	All colors	Mixed to diffuse	10-90	G	G	G	G	G	Slow burn
Baked clear coatings	D, B, S	A, P	Colorless, clear color	Diffuse to specular	0	G	G	G	G	G	Slow burn
Organic sol	D, S	A, P	All colors	Mixed to diffuse	10-90	F	E	G	G	F	None
Ceramic coatings											
Vitreous enamels	D, S	A, P, R	All colors	Diffuse to specular	10-90	E	E	E	P	E	None
Ceramic enamels	D, S, B	A, R	All colors	Mixed to specular	10-90	E	E	E	P	E	None
Metallic coatings											
Chrome plate	Electrochemical	A, P	Fixed; depending on color of plated metal	Specular to diffuse	60-88	E	E	E	E	E	None
Nickel plate	Electrochemical	A, P		Specular to diffuse	55	E	G	E	E	E	None
Cadmium plate	Electrochemical	P		Specular to diffuse	85	G	G	F	P	E	None
Brass plate	Electrochemical	A		Specular to diffuse	55-80	P	P	F	P	F	None
Silver plate	Electrochemical	A, R		Specular	85-95	P	P	F	P	E	None
Laminates	Laminate	A, P, R	All colors of metallic effects	Mixed	10-90	Depends on nature of laminate				Slow burn	
Conversion coatings											
Anodized aluminum	Electrochemical	A, P, R	Natural aluminum (or a wide variety of colors)	Diffuse to specular	60-90	E	E	E	E	E	None
Vacuum metalizing											
	Vacuum chamber	A, R	Natural aluminum (or a wide variety of colors)	Specular	10-70	Depends on nature of protective coating				None	
Vacuum deposition											
	Vacuum chamber	A, R, T	Colorless to interference effects	Diffuse to specular	0-99	E	E	E	E	E	None

^a D—dip, S—spray, B—brush.^b A—appearance, P—protection, R—reflectance, T—transmittance.^c P—poor, F—fair, G—good, E—excellent.^d Depends on color.