

and chuck are rotating, the metal is forced against the chuck by means of a tool held by the operator. The blank assumes the shape of the chuck. Automatic equipment exists that forms the metal against the chuck by means of rollers. This is called autospinning. This process is characterized by low tool investment. Manual spinning usually is performed only for low quantities and for special or prototype pieces.

Stamping. Also known as drawing or deep drawing, this metal-forming process places a metal blank on top of a negative cavity die, usually a cast block of steel. While the perimeter of the blank is held firmly by a ring, a positive die forces the blank into the negative cavity. The blank assumes the shape of the matching positive and negative dies. This process is characterized by high tool and setup costs, but low piece costs in high-volume production.

Hydroforming. In this process a metal blank is placed on a die plate and forced against a diaphragm of synthetic material, behind which is a large container filled with oil. The oil container is called the pressure dome. A positive die is forced against the metal blank. The oil is nearly incompressible and helps form the metal blank to the shape of the die. Water, rather than oil, was originally used in this process; thus its name. This process is characterized by low tool costs and low piece costs in high-volume production.

Die Casting. In this process molten metal is pumped at high pressure into a two-piece die. The die halves open when the part is sufficiently cooled, and ejector pins push the part out of one of the die halves. This process is characterized by very high tool costs but low piece costs in very high volume production.

Plastics. The forming and converting of plastics into end products is a highly specialized field. Some of the more important processes are as follows:

- Injection molding: Fluid plastic is forced under pressure into a controlled-temperature mold.
- Compression molding: Resin is placed in the mold, and the cavity is filled by application of heat and pressure.
- Blow molding: A thin cylinder of plastic is placed in a mold and inflated by air pressure to conformity with the mold cavity.
- Extrusion: Fluid plastic is forced through a die.
- Thermoforming: A sheet, heated to a state of limpness, is draped over a mold and forced into close conformity with it by pressure or vacuum.
- Spray coating: A solution or emulsion is sprayed on a prepared surface.
- Machining: Solid plastic is shaped by usual wood- or metal-working operations.
- Rotational molding: Resin is charged into a mold rotated in an oven, centrifugal forces distribute the resin, and the heat melts and fuses the charge to the shape of the cavity.
- Cold stamping: Cold plastic sheets are stamped and formed.
- Ultrasonic welding: Plastics are bonded by conversion of sonic vibrations to heat.
- Coextrusion: Two compatible plastics are extruded simultaneously to produce a finished profile. This is performed with a twin-head extruding machine.
- Two-color molding: One part is molded and a second material is injected into designated areas of the part. This method uses a twin-head injection molding machine, or two machines and dies.
- Transfer molding: A decorating film or ink is placed on a tape, which is spooled through the mold. The tape indexes to the desired position, and the material is then injected into the mold, against the underside of the tape. When the mold opens for ejection of the part, the tape is stripped away, leaving a completed, decorated part.

Secondary operations for molded plastics include vacuum metallizing for reflectors, painting, silk-screening, hot stamping, decorative or protective pad printing, plating for chemical resistance, sonic welding for bonding, laser cutting for hole piercing or machining, and the use of high-pressure water jets for custom fabrication. Dichroic coating can be applied to some plastic materials to produce cold-mirror reflectors.

Glass. Glass may be formed by several techniques: pressing, blowing, rolling, drawing, centrifugal casting, and sagging. These operations may be performed by hand methods or by automatic machines, depending on volume. After being formed, many glass products must be annealed to relieve excessive stress. Additional finishing operations may be required, such as cutting, grinding, polishing, and drilling. Further treatment, such as tempering or chemical strengthening, may be required to obtain the desired physical properties.

The finishes for glass surfaces are varied in nature, depending on the forming technique. The surfaces may be subsequently altered by chemical etching, sandblasting or shot blasting, polish staining, and coating. These operations are used to obtain reflection, control radiation, or make a surface electrically conductive.

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Daylighting

Daylight¹ is distinguished as a light source by its unique, changing spectra and distributions. It can increase occupant satisfaction and conserve energy if considerations such as view design, glare control, human factors, and integration of building systems are properly addressed. It is essential that daylight effects be considered in any space where daylight is admitted, even if it is not exploited as a light source, in order to avoid problems with glare and damage to materials.

To use daylight effectively, the following factors should be taken into account:

- Human factors, including physiology, perception, preferences, and behavior
- Effects of daylight on all materials, including furniture, artwork, and plants
- Controlled admission of direct sunlight
- Controlled admission of diffuse daylight
- Effects of local terrain, landscaping, and nearby buildings on the available light
- Integration of building systems, including the electric lighting, fenestration, interior geometry and finishes, manual and automatic control systems, and active climate control systems

DAYLIGHT SOURCES AND AVAILABILITY

The daily and seasonal movements of the sun with respect to a particular geographic location on the earth produce a predictable pattern of amount and direction of available daylight. Superimposed on this predictable pattern is variation caused by changes in the weather, temperature, and air pollution.

Of the solar energy received at the earth's surface, 40% is visible radiation. The rest is ultraviolet (UV) and infrared (IR) wavelengths. When absorbed, virtually all the radiant energy from the sun is converted to heat. The amount of usable visible energy in the solar spectrum varies with the depth and condition of the atmosphere through which the light traverses. Because the spectral distribution of daylight changes continuously with sun position and sky conditions, the Commission Internationale de l'Éclairage (CIE) has adopted three standard spectral radiant power distributions for daylight (Figure 8-1).

The Sun as a Light Source

The rotation of the earth about its axis, as well as its revolution about the sun, produces an apparent motion of the sun

with respect to any point on the earth's surface. The position of the sun with respect to such a point is expressed in terms of two angles: the solar altitude, which is the vertical angle of the sun above the horizon, and the solar azimuth, which is the horizontal angle of the sun from due south in the northern hemisphere (Figure 8-2). See Chapter 1, *Light and Optics*, for the average luminance of the sun and the illuminance of the earth's surface by the sun.

The Sky as a Light Source

As sunlight passes through the atmosphere, a portion is scattered by dust, water vapor, and other suspended particles. This scattering, acting in concert with clouds, produces sky luminance. Skies are divided into three categories: (1) clear, (2) partly cloudy, and (3) overcast. When the sky is not completely overcast, the sky luminance distribution may change rapidly and by a large amount as the sun is alternately obscured, partly obscured, or fully revealed.

The Ground as a Light Source

Light reflected from the ground may be important in daylighting design. Such light is, in turn, reflected from the ceiling or walls onto other interior surfaces. On daylighted elevations, the light reflected from the ground typically represents 10 to 15% of the total daylight reaching a window. It frequently exceeds this with light-colored ground surfaces such as sand and snow. On shaded exposures, it may account for even more of the total light reaching a window, depending on the sky condition and building design.

Daylight Availability

Lighting calculations for daylighting can be considerably more complex than for electric lighting. Determination of the illuminance incident on windows and skylights must take into account the time-varying characteristics of the sky and sun, including the changing spatial relationship between the sun and daylighting apertures.

The phrase "daylight availability" refers to the amount of light from the sun and the sky for a specific location, time, date, and sky condition. Over the past 60 years measurements of daylight illuminance by researchers in locations all over the world have resulted in very similar mean values.² Equations giving available daylight illuminance are determined from these values.

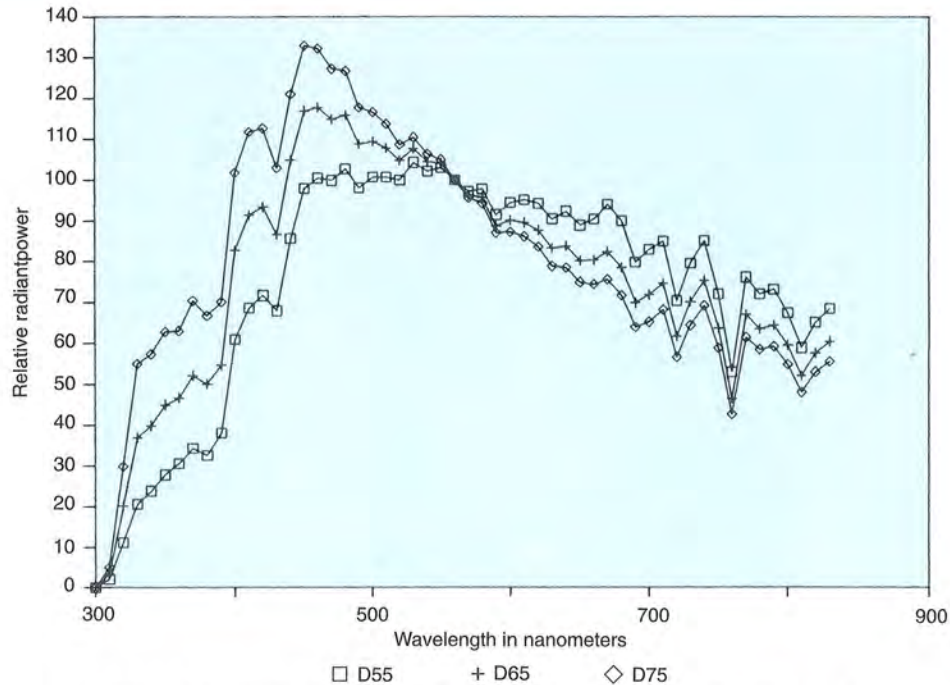


Figure 8-1. Three spectral radiant power distributions of daylight, developed by the CIE, daylight at 5500K (D_{55}), 6500K (D_{65}), and 7500K (D_{75}).

Daylight availability data, and the equations derived from them, do not express instantaneous values of illuminance and luminance; they give mean values. In other words, the equations provide best fits to data averaged over time and measurement sessions. For this reason, measured instantaneous luminances and illuminances may differ widely from those determined by calculation methods

based on daylight availability. It is not unusual for the instantaneous values to be more than twice or less than half the mean design values.

Calculation of daylight availability at a site begins with a determination of the solar position, which is a function of latitude and longitude of the site, day of the year (Julian date), and local time.³ The local time is converted to solar time. Angles are computed that give the position of the sun in the sky. Finally, for a particular sky condition, the daylight availability equations are used to compute the daylight illuminance. All angles are expressed in radians.

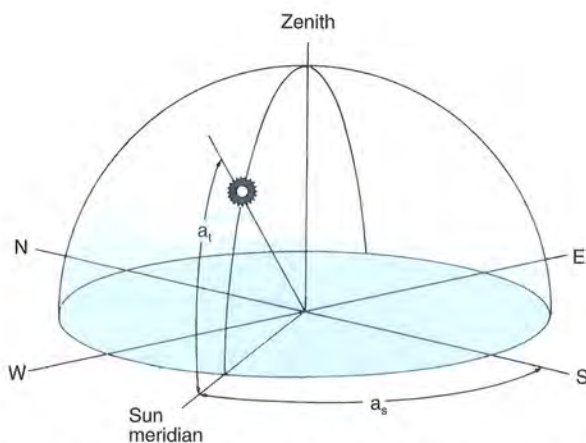


Figure 8-2. The sun's position in terms of solar altitude (a_i) and azimuth (a_s) with respect to the cardinal points of the compass.

Site Location

The site location is specified by a latitude l and a longitude L . Latitudes and longitudes may be found in any standard atlas or almanac. Figure 8-3 shows the latitudes and longitudes of some North American cities.⁴

Conventions used in expressing latitudes are:

Positive = northern hemisphere
Negative = southern hemisphere

Conventions used in expressing longitudes are:

Positive = west of prime meridian (Greenwich, United Kingdom)
Negative = east of prime meridian

Figure 8-3. Latitude and Longitude of Some North American Cities

Country/City	Latitude		Longitude	
	Degrees	Radians	Degrees	Radians
Canada				
Ottawa, ON	45	0.79	76	1.33
Montreal, PQ	46	0.80	74	1.29
Toronto, ON	44	0.77	79	1.38
Vancouver, BC	49	0.85	123	2.15
Winnipeg, MB	50	0.87	97	1.69
Mexico				
Mexico City	19	0.33	99	1.73
United States				
Anchorage, AK	61	1.06	150	2.62
Big Rapids, MI	44	0.77	85	1.48
Boulder, CO	40	0.70	105	1.83
Chicago, IL	42	0.73	88	1.54
Cleveland, OH	41	0.72	82	1.43
Dallas, TX	33	0.58	97	1.69
Honolulu, HI	21	0.37	158	2.76
Los Angeles, CA	34	0.59	118	2.06
Miami, FL	26	0.45	80	1.40
New York, NY	41	0.72	74	1.29
Philadelphia, PA	40	0.70	75	1.31
Seattle, WA	48	0.84	122	2.13
Troy, NY	43	0.75	74	1.29
Washington, DC	39	0.68	77	1.34

Time

A 24h clock is used to express time. Solar time can be determined from standard time (or daylight time) by correcting both for site longitude within a time zone and for the equation of time. The equation of time gives the difference between solar time and clock time due to elliptical orbit of the earth and solar declination of the axis. The value for the equation of time may be determined from:⁵

$$ET = 7.637 \sin\left(\frac{2\pi(J - 2.5)}{365.25}\right) - 9.863 \sin\left(\frac{2\pi(J - 81.6)}{365.25}\right) \frac{1}{60} \quad (8-1)$$

where

ET = time expressed in decimal hours (for example, 1:30 p.m. = 13.5),
J = Julian date, a number between 1 and 365.

This equation is accurate to within 5 degrees and suitable for most terrestrial daylighting calculations. If an application requires more accuracy, the equation by Meeus⁶ may be used.

Each time zone has a reference longitude that is used in calculating solar time. These standard meridians are given in Figure 8-4.

The relationship between standard time and daylight time is given by

Figure 8-4. Time Zone Standard Meridians

Time Zone	Standard Meridian	
	Degrees	Radians
Atlantic	60	1.05
Eastern	75	1.31
Central	90	1.57
Mountain	105	1.83
Pacific	120	2.09
Yukon	135	2.36
Alaskan-Hawaiian	150	2.62
Bering	165	2.88

$$t_s = t_d - 1 \quad (8-2)$$

where t_s is standard time in decimal hours and t_d is daylight time in decimal hours.

Solar time is calculated from standard time by the equation

$$t = t_s + ET + \frac{12(SM - L)}{\pi} \quad (8-3)$$

where

t = solar time in decimal hours,
 t_s = standard time in decimal hours,
ET = time from equation 8-1 in decimal hours,
SM = standard meridian for the time zone in radians,
 L = site longitude in radians.

Solar Position

The position of the sun is specified by the solar altitude and solar azimuth and is a function of site latitude, solar time, and solar declination. The solar declination can be closely approximated by

$$\delta = 0.4093 \sin\left(\frac{2\pi(J - 81)}{368}\right) \quad (8-4)$$

where

δ = solar declination in radians,
J = Julian date.

The solar altitude is given by

$$a_t = \arcsin\left(\sin l \sin \delta - \cos l \cos \delta \cos \frac{\pi t}{12}\right) \quad (8-5)$$

where

a_t = solar altitude in radians,
 l = site latitude in radians,
 δ = solar declination in radians,
 t = solar time in decimal hours.

The solar altitude has a range of 0 to $\pi/2$. If the sun is below the horizon, Equation 8-5 gives a negative value. The solar azimuth is given by

$$a_s = \arctan \left(\frac{-\left[\cos \delta \sin \left(\frac{\pi t}{12}\right)\right]}{-\left[\cos l \sin \delta + \sin l \cos \delta \cos \left(\frac{\pi t}{12}\right)\right]} \right) \quad (8-6)$$

where a_s is the solar azimuth in radians; the other variables are the same as in Equation 8-5. Positive solar azimuthal angles indicate a direction west of south, and negative angles indicate a direction east of south. The arctangent must be placed in the proper quadrant by assessing the signs of the numerator and denominator of its argument.

In many daylighting calculations, it is necessary to calculate the daylight on a vertical surface such as a wall or a window. The elevation azimuth angle is needed for this calculation. It is the angle, measured in the horizontal plane, between the normal to the vertical surface and south (in the northern hemisphere) (Figure 8-5). It is measured clockwise from south.

The solar elevation azimuth gives the azimuthal angle between the sun and the normal to a vertical surface of interest (Figure 8-5). It is given by

$$a_z = a_s - a_e \quad (8-7)$$

where

$$\begin{aligned} a_z &= \text{solar elevation azimuth in radians,} \\ a_s &= \text{solar azimuth in radians,} \\ a_e &= \text{elevation azimuth in radians.} \end{aligned}$$

The incident angle is the angle between the normal to a vertical surface of interest and the direction to the sun (Figure 8-6) and can be computed from

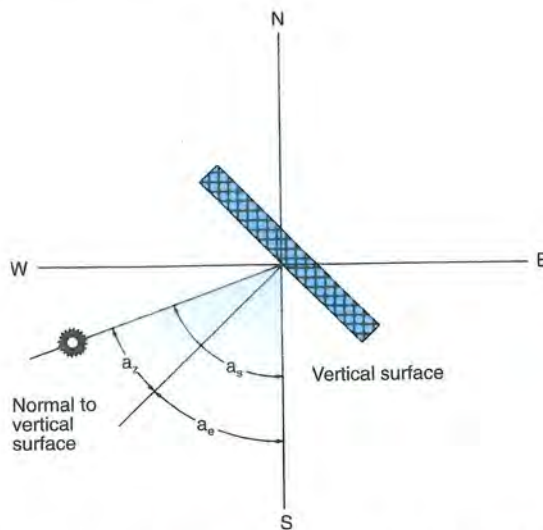


Figure 8-5. Azimuth angles (plan view). See Equation 8-7.

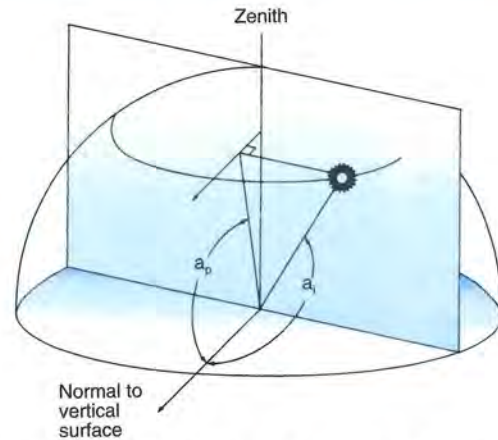


Figure 8-6. Incident and profile angles. See Equations 8-8 and 8-9.

$$a_i = \arccos(\cos a_t \cos a_z) \quad (8-8)$$

where

$$\begin{aligned} a_i &= \text{incident angle in radians,} \\ a_t &= \text{solar altitude in radians,} \\ a_z &= \text{solar elevation azimuth in radians.} \end{aligned}$$

The profile angle is the apparent altitude of the sun relative to a vertical surface of interest (Figure 8-6) and is calculated by Equation 8-9a or 8-9b below. It is used primarily to determine shadows and to plot sunlight penetration on building sections:

$$a_p = \arctan \left(\frac{\sin a_t}{\cos a_i} \right) \quad (8-9a)$$

$$a_p = \arctan \left(\frac{\tan a_t}{\cos a_z} \right) \quad (8-9b)$$

where

$$\begin{aligned} a_p &= \text{profile angle in radians,} \\ a_t &= \text{solar altitude in radians,} \\ a_i &= \text{incident angle in radians,} \\ a_z &= \text{solar elevation azimuth in radians.} \end{aligned}$$

Sunlight

For the purpose of most basic daylighting calculations, the sun is considered to be a point source that provides a constant illuminance at a point on a plane that is normal to the direction of the sun and near the earth's orbit. The solar illumination constant is the total solar illuminance at normal incidence on a surface in free space at the earth's mean distance from the sun. It is obtained from

$$E_{sc} = K_m \int_{380}^{770} G_\lambda V_\lambda d\lambda \quad (8-10)$$

where

E_{sc} = solar illumination constant in klx,

K_m = spectral luminous efficacy of radiant solar flux in lm/W,

$G(\lambda)$ = solar spectral irradiance at wavelength λ , in W,

$V(\lambda)$ = photopic vision spectral luminous efficiency at wavelength λ ,

λ = wavelength in nm (for photopic vision at 380 to 770 nm).

The following are important solar parameters based on current standards:^{7,8}

Solar illumination constant: 128 klx

Solar irradiation constant: 1350 W/m² (126 W/ft²)

Solar luminous efficacy: 94.2 lm/W

To calculate the sunlight reaching the ground, two conditions must be considered: the varying distance of the earth to the sun caused by the earth's elliptical orbit and the effect of the earth's atmosphere. The extraterrestrial solar illuminance, corrected for the earth's elliptical orbit, is

$$E_{xt} = E_{sc} \left(1 + 0.034 \cos \frac{2\pi(J-2)}{365} \right) \quad (8-11)$$

where

E_{xt} = extraterrestrial solar illuminance in klx,

E_{sc} = solar illumination constant in klx,

J = Julian date.

The direct normal illuminance at sea level, E_{dn} , corrected for the attenuating effects of the atmosphere, is given by⁹

$$E_{dn} = E_{xt} e^{-cm} \quad (8-12)$$

where

E_{dn} = direct normal solar illuminance in klx,

E_{xt} = extraterrestrial solar illuminance in klx,

c = atmospheric extinction coefficient (Figure 8-7),

m = optical air mass (dimensionless).

Values for the atmospheric extinction coefficient, discussed below, vary with the sky condition. The equation that is the simplest and the most often used¹⁰ representation for the optical air mass is

$$m = \frac{1}{\sin a_t} \quad (8-13)$$

where m is the optical air mass (dimensionless) and a_t is the solar altitude in radians. The direct sunlight on a horizontal plane is expressed by

$$E_{dh} = E_{dn} \sin a_t \quad (8-14)$$

where

E_{dh} = direct horizontal solar illuminance in klx,

E_{dn} = direct normal solar illuminance in klx,

a_t = solar altitude in radians.

The direct sunlight on a vertical elevation is expressed by

$$E_{dv} = E_{dn} \cos a_i \quad (8-15)$$

where

E_{dv} = direct vertical solar illuminance in klx,

E_{dn} = direct normal solar illuminance in klx,

a_i = incident angle in radians.

Skylight

Either the sky-ratio method or the sky-cover method is used to classify a sky. The sky ratio is determined by dividing the horizontal sky irradiance by the global horizontal irradiance. Since the sky ratio approaches 1.0 when the solar altitude approaches zero (regardless of the sky condition), this method is not accurate for low solar altitudes. The sky conditions are defined as follows:

Clear:	sky ratio ≤ 0.3
Partly cloudy:	$0.3 < \text{sky ratio} < 0.8$
Overcast:	$0.8 \leq \text{sky ratio}$

The sky cover method uses estimates of the amount of cloud cover. Cloud cover is estimated in tenths and is expressed on a scale from 0.0 for no clouds to 1.0 for complete sky cover. The sky conditions are as follows:

Clear	0.0 to 0.3
Partly cloudy	0.4 to 0.7
Overcast	0.8 to 1.0

The horizontal illuminance produced by the sky can be expressed as a function of solar altitude:²

$$E_{kh} = A + B \sin^C a_t \quad (8-16)$$

where

E_{kh} = horizontal illuminance due to unobstructed skylight in klx,

A = sunrise/sunset illuminance in klx,

B = solar altitude illuminance coefficient in klx,

C = solar altitude illuminance exponent,

a_t = solar altitude in radians.

The form of the equation is the same for all three sky conditions, with different constants for different sky conditions (Figure 8-7).

Figure 8-7. Daylight Availability Constants*

Sky Condition	c	A (klx)	B (klx)	C
Clear	0.21	0.8	15.5	0.5
Partly Cloudy	0.80	0.3	45.0	1.0
Cloudy	†	0.3	21.0	1.0

* See Equations 8-12 and 8-16.

† No direct sun; $E_{dn} = 0$.

A different equation is used to represent the mean luminance distribution of each of the three sky conditions. The luminance of the sky is a function of luminance distribution with respect to zenith luminance and absolute value of the zenith luminance. In the method used here, a zenith luminance factor is used to calculate the zenith luminance from the horizontal sky illuminance:

$$L_z = E_{kh} ZL \quad (8-17)$$

where

L_z = zenith luminance in kcd/m²,

E_{kh} = horizontal illuminance due to unobstructed skylight from Equation 8-16, in klx,

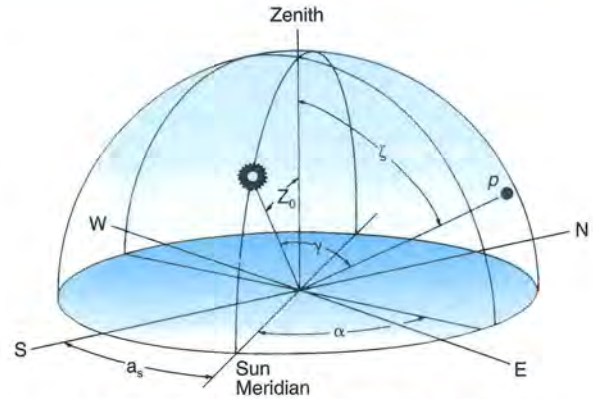
ZL = zenith luminance factor at the same solar altitude as E_{kh} , in kcd/(m²klx).

Values for the zenith luminance factor can be found in Figure 8-8. More detailed equations for the zenith luminance

Figure 8-8. Sky Zenith Luminance (ZL) Constants

Solar Altitude (degrees)	Clear Sky ZL	Partly Cloudy Sky ZL
90	1.034	.637
85	.825	.567
80	.664	.501
75	.541	.457
70	.445	.413
65	.371	.375
60	.314	.343
55	.269	.315
50	.234	.292
45	.206	.272
40	.185	.255
35	.169	.241
30	.156	.230
25	.148	.221
20	.142	.214
15	.139	.209
10	.139	.205
5	.140	.202
0	.144	.201

For overcast sky, $ZL = 0.409$ for any Solar Altitude.

**Figure 8-9.** Sky angles. See Equation 8-19 and Figure 8-2.

have been developed, which include effects such as differences in atmospheric turbidity.¹¹

The angles used in sky luminance determinations are shown in Figure 8-9. The position of the sun in Figure 8-9 is given by the solar azimuth a_s and zenithal sun angle Z_0 . Note that Z_0 is related to the solar altitude a_t by the simple formula

$$Z_0 = \frac{\pi}{2} - a_t \quad (8-18)$$

The position of a point p in the sky (at which the sky luminance is calculated) is given by angles z , the zenithal point angle in radians, and ξ , the azimuth angle from the sun in radians.

A standard clearsky luminance distribution function was developed by Kittler¹² and adopted by the CIE:¹³

$$L(\xi, \alpha) = L_z \frac{(0.91 + 10 e^{-3\gamma} + 0.45 \cos^2 \gamma)(1 - e^{-0.32/\cos \xi})}{(0.91 + 10 e^{-3Z_0} + 0.45 \cos^2 Z_0)(1 - e^{-0.32})} \quad (8-19)$$

where

$L(\xi, \alpha)$ = sky luminance at point p with spherical coordinates ξ and α , in kcd/m²,

L_z = sky zenith luminance in kcd/m²,

γ = angle between the sun and sky point p in rad (Equation 8-20),

ξ = zenithal point angle in radians,

α = azimuth angle from the sun in radians,

Z_0 = zenithal sun angle in radians.

The angle γ between the sun and sky point p is given by

$$\gamma = \arccos (\cos Z_0 \cos \xi + \sin Z_0 \sin \xi \cos \alpha) \quad (8-20)$$

where

Z_0 , γ , ξ , and α are defined as in Equation 8-19. This equation does not take account of changes in the luminance dis-

tribution due to changes in atmospheric turbidity, which can substantially alter the luminance distribution of the sky.

The equation for a partly cloudy sky¹⁴ is similar in form to the clear-sky distribution but has different values of the constants based on mean data for partly cloudy skies:

$$L(\zeta, \alpha) = L_z \frac{(0.526 + 5 e^{-1.5\gamma})(1 - e^{-0.80/\cos \zeta})}{(0.526 + 5 e^{-1.5z_0})(1 - e^{-0.80})} \quad (8-21)$$

where the symbols have the same meaning as in Equation 8-19. The overcast-sky equation is

$$L(\zeta, \alpha) = L_z \left(0.864 \frac{e^{-0.52/\cos \zeta}}{e^{-0.52}} + 0.136 \frac{1 - e^{-0.52/\cos \zeta}}{e^{-0.52}} \right) \quad (8-22)$$

The form of the overcast-sky equation can be derived from first principles.¹³ The first term provides the luminance contribution of the cloud layer, and the second term provides the luminance contribution of the atmosphere between the bottom of the cloud layer and the ground. Constants have been chosen to give a best fit to the original data used by Moon and Spencer¹⁵ in their treatment of the overcast sky.

The empirical Moon-Spencer¹⁵ equation for the luminance distribution of an overcast sky is

$$L(\zeta, \alpha) = \frac{L_z}{3} (1 + 2 \cos \zeta) \quad (8-23)$$

where

$$\begin{aligned} L(\zeta, \alpha) &= \text{sky luminance in kcd/m}^2, \\ L_z &= \text{sky zenith luminance in kcd/m}^2, \\ \zeta &= \text{zenithal point angle in radians.} \end{aligned}$$

This equation has been almost universally used to represent overcast skies for the past 40 years and was adopted by the CIE in 1955.¹⁶ It is historically significant in that a large number of daylight calculation methods are based on it. There is very little numerical difference between Equations 8-22 and 8-23 for the appropriate constants.

The illuminance on a horizontal surface produced by a differential element of the sky is given by

$$dE_{kh} = L(\zeta, \alpha) \cos \zeta d\omega = L(\zeta, \alpha) \cos \zeta \sin \zeta d\zeta d\alpha \quad (8-24a)$$

where

$$\begin{aligned} E_{kh} &= \text{illuminance on the horizontal surface in klx,} \\ L(\zeta, \alpha) &= \text{sky luminance at point } p \text{ with spherical coordinates } \zeta \text{ and } \alpha, \text{ in kcd/m}^2, \\ d\omega &= \text{differential element of solid angle in the direction to point } p, \\ \zeta &= \text{zenithal point angle in radians,} \\ \alpha &= \text{azimuth angle from the sun in radians.} \end{aligned}$$

This equation assumes spherical coordinates. It can be integrated to give the horizontal illuminance produced by an area of sky:

$$E_{kh} = \iint L(\zeta, \alpha) \sin \zeta \cos \zeta d\zeta d\alpha \quad (8-24b)$$

where

$$\begin{aligned} E_{kh} &= \text{illuminance on the horizontal surface in klx,} \\ L(\zeta, \alpha) &= \text{sky luminance at point } p \text{ with spherical coordinates } \zeta \text{ and } \alpha, \text{ in kcd/m}^2, \\ d\omega &= \text{differential element of solid angle in the direction to point } p, \\ \zeta &= \text{zenithal point angle in radians,} \\ \alpha &= \text{azimuth angle from the sun in radians.} \end{aligned}$$

The limits of integration depend on the position and extent of the sky patch. In the limit of the entire sky, the integration is over a hemisphere. This gives

$$E_{kh} = \int_0^{2\pi} \int_0^{\pi/2} L(\zeta, \alpha) \sin \zeta \cos \zeta d\zeta d\alpha \quad (8-25)$$

Similarly, the illuminance on a vertical surface due to the sky only is given by

$$E_{kv} = \int_{\alpha_z - \pi/2}^{\alpha_z + \pi/2} \int_0^{\pi/2} L(\zeta, \alpha) \sin^2 \zeta \cos \alpha d\zeta d\alpha \quad (8-26)$$

In numerical methods, Equations 8-25 and 8-26 are usually approximated by finite sums of products of differentials and discrete values.

For those cases where the illuminance is desired at a point on a horizontal or vertical plane that has unobstructed access to the sky and the sun, illuminances for given sky conditions and sun positions can be obtained from graphs based on Equations 8-25 and 8-26 (Figures 8-10 through 8-17).

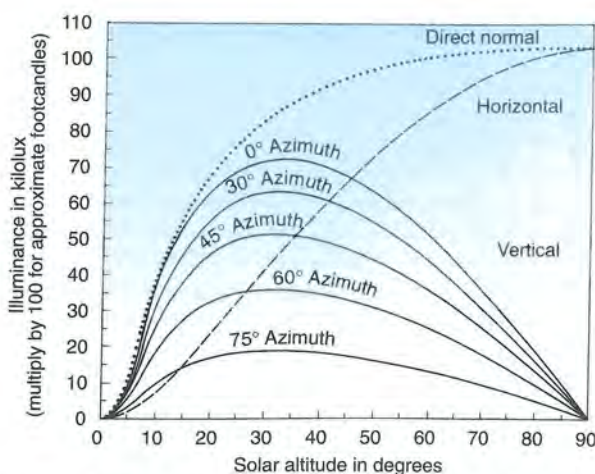


Figure 8-10. Illuminance from the sun under clear sky conditions as a function of solar altitude and azimuth.

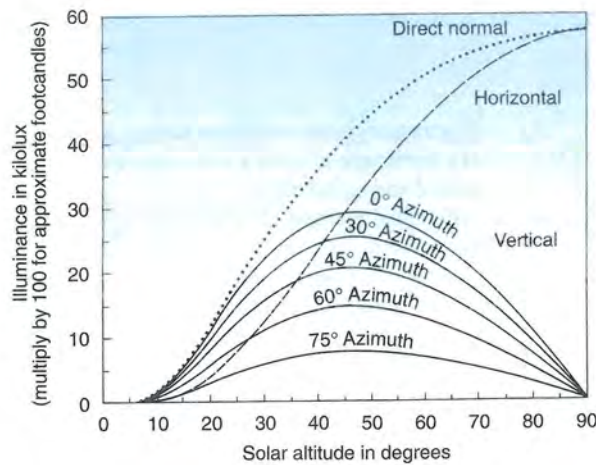


Figure 8-11. Illuminance from the sun under partly cloudy sky conditions as a function of solar altitude and azimuth.

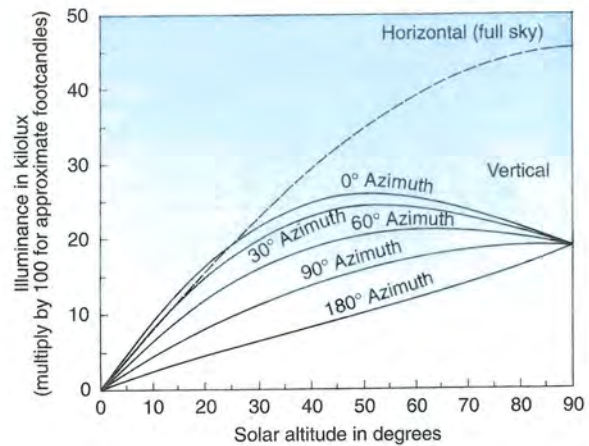


Figure 8-13. Illuminance on vertical surfaces from partly cloudy sky conditions as a function of solar altitude and azimuth.

DAYLIGHTING AND HUMAN FACTORS

View Design and Human Reaction to Windows

It is important that the provision of view and the delivery of daylight be clearly differentiated. Although the terms “view” and “daylighting” are sometimes used interchangeably, the view function of windows is very different from the daylight delivery function. The provision of daylight alone (for example, through skylights) will not satisfy user desires for views including sky, horizon, and ground.¹⁷

It has been suggested that, to satisfy most workers, win-

dows must cover at least 20% of the window wall area.¹⁸⁻²⁰ Heavily tinted glass, used to reduce glare and solar heat gain from such windows, gives outdoor areas an overcast and gloomy appearance, even on sunny days.²¹

Glare from Daylight

Daylighting systems can produce discomfort glare.²² Very high luminance ratios are produced unless care is taken to balance and reduce luminances. Increased interior electric lighting may be required to balance luminances and reduce glare produced by daylight, thus increasing energy use when daylighting is used. Glare is critically dependent on the lu-

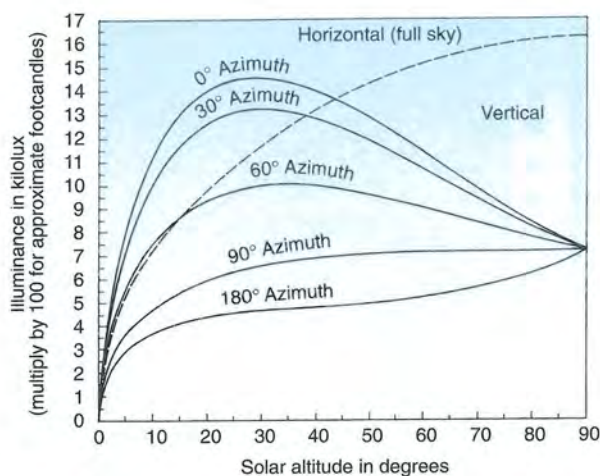


Figure 8-12. Illuminance on vertical surfaces from clear sky conditions as a function of solar altitude and azimuth.

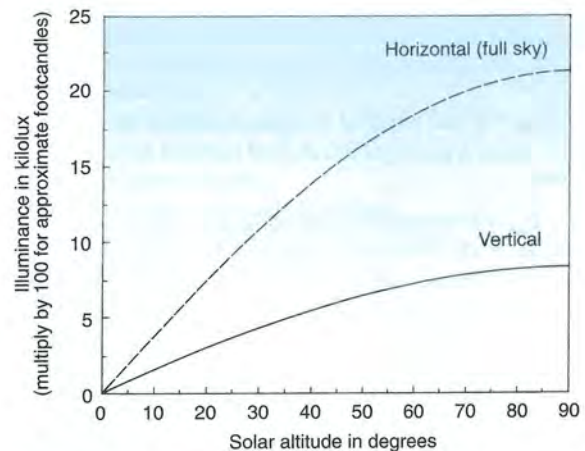


Figure 8-14. Illuminance on vertical surfaces from overcast sky conditions as a function of solar altitude.

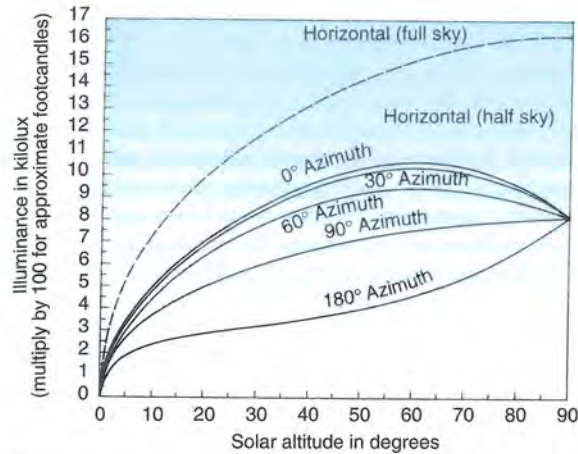


Figure 8-15. Illuminance on horizontal surfaces from clear sky conditions as a function of solar altitude and azimuth.

minance of the window. Methods for predicting the presence of glare from large area sources have been developed.²³

Because of its intensity, direct sunlight also must be considered in glare control. While it may be used as an amenity, it should be excluded from critical task areas. The duration of sunlight, rather than its intensity or the size of the illuminated patch, correlates best with the appreciation of interior sunlight.²⁴⁻²⁶

Human Behavior with Respect to Blinds and Shades

Venetian blinds and curtains are commonly used devices for adjusting the amount of daylight entering spaces and reduc-

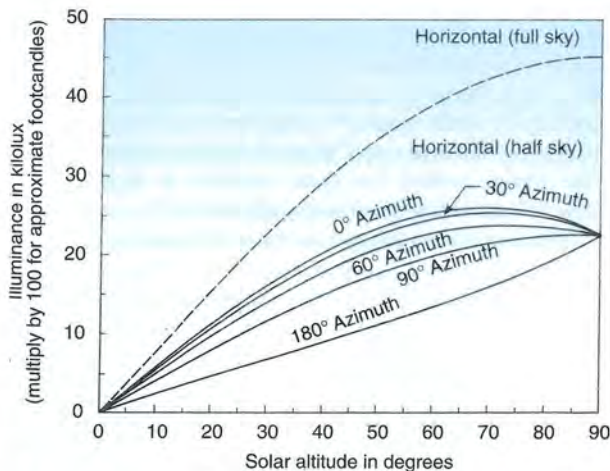


Figure 8-16. Illuminance on horizontal surfaces from partly cloudy sky conditions as a function of solar altitude and azimuth.

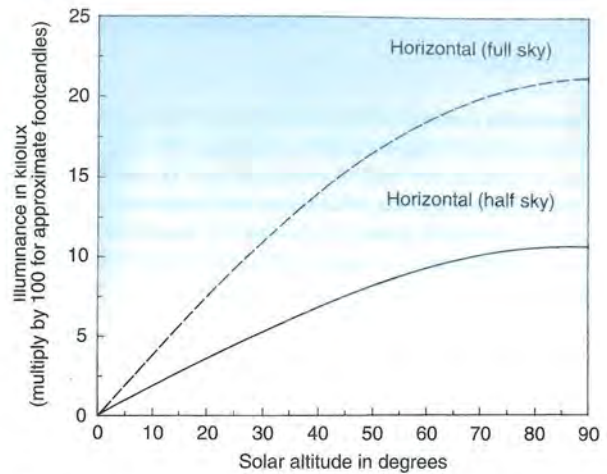


Figure 8-17. Illuminance on horizontal surface from overcast sky conditions as a function of solar altitude.

ing window luminance to control glare. These devices can drastically reduce the amount of daylight admitted to a space, so occupant use of blinds is an important consideration in estimating energy savings from daylighting. Occupants adjust venetian blinds infrequently, having preferred blind positions that are dependent on the orientation of the facade and the season of the year.²⁷⁻²⁹

DAYLIGHT EFFECTS ON BUILDING CONTENTS

Daylight Effects on Materials and Artwork

Daylight is of particular concern with respect to light damage to materials and artwork because of its high intensity relative to light from electric sources. Light at all wavelengths, not just in the UV range, contributes to fading, bleaching, and other damage.³⁰ However, UV is known to be especially active in the fading and bleaching process. Unfiltered daylight has about ten times as much UV radiation per lumen as light from incandescent lamps. The length of time that materials are exposed to daylight is a factor in fading; the longer the exposure time, the greater the damage. Exposure of items such as sensitive display merchandise to daylight should therefore be minimized. Fading and bleaching are discussed in Chapter 5, Nonvisual Effects of Optical Radiation, and in Chapter 14, Lighting for Public Spaces.

Daylight Effects on Plants

Daylight provides the full spectrum that plants need for all photoresponses in order to maintain health. Lighting for plant health is discussed in Chapter 5, Nonvisual Effects of Optical Radiation.

CALCULATION OF INTERIOR ILLUMINANCES

Calculation methods are useful in comparing alternative daylight delivery systems or considering the limits of daylight utilization for various buildings and systems under a wide variety of lighting conditions. Calculation methods are useful alternatives when weather or sky conditions do not permit appropriate or comparable scale model measurements and evaluation.

Manual Methods

Manual methods for calculating illuminance at a point involve determination of the sky, sun, and interreflected components of daylight. The sky and sun components are computed from flux that reaches a window aperture or point directly. The interreflected component results from sunlight and skylight that have initially reached other surfaces and have then been reflected to the point of interest. Methods for determining the direct and interreflected components of illuminance at a point are described in Chapter 9, Lighting Calculations. Average illuminance on a workplane can be calculated using the lumen methods described below.

Computer Calculations³¹⁻³⁵

Because of the speed with which design alternatives can be explored and the complexity that can be evaluated, computer-based daylight calculations are important design tools. Capabilities for visualization of interior scenes with combined electric sources and daylighting are included with many software packages.^{33,36-38}

Calculations of point illuminance are usually made with computer software because of the capacity to model electric lighting and to calculate lighting energy savings, which may be problematic with scale models and other manual methods. There are two basic approaches to the computer computation of daylight: radiative transfer and ray tracing. These methods are described in detail in Chapter 9, Lighting Calculations.

With radiative transfer-based computer programs, the sky and sun components at the points of interest are determined using a finite-sum approximation for Equations 8-25 and 8-26. The summation is performed using only those (small) sections of the sky that illuminate the points directly. The interreflected component of illuminance is determined using the finite element radiative transfer method. This process is described in detail in Chapter 9, Lighting Calculations. In its application to daylight calculations, the initial exitances of room surfaces are determined from the flux input from windows and skylights. Most radiative transfer methods assume that room surface reflectances are diffuse. Hybrid flux transfer programs that provide for the display of specular highlights often use a second pass of the scene to add gloss to the surfaces.

Because the flux-transfer approach bases its calculation on a finite-element analysis of the surfaces of the scene, calculation of the direct and interreflected components can become very complicated for elaborate fenestration and skylight systems if space contents are to be modeled (for example, partitions and furniture) or if the space geometry is complicated. There is a logarithmic relationship between geometric complexity (number of surfaces) and computer resources necessary to complete the calculations. Ray tracing is inherently slower for geometrically simple spaces but is capable of handling almost unlimited geometric complexity with a sublinear relationship to computer resource requirements (Chapter 9, Lighting Calculations.)

The utility of the computational technique is usually dictated by the nature of the information required. If illuminances at points are the only requirement, a radiative transfer procedure is usually sufficient. If accurate and realistic visualization of a space is required, ray tracing can be the better technique. The advantage of radiative transfer is that one computation allows for all views of the room to be readily redisplayed without additional computations, facilitating a simulation of a walk-through of the space. Several commercially available programs use this technique.^{33,36-38} The advantage of ray tracing is that nondiffuse surfaces and greater geometric complexity are inherently more accurately and easily calculated. Programs using this technique are also available.³³ The software packages most successful at solving real-world problems usually employ a hybrid of these methods. Factors affecting the accuracy of computer simulations are discussed in References 39 and 40.

Lumen Method⁴¹

The lumen method for calculation of interior illuminances is similar to the zonal cavity method for electric lighting and is simple enough to permit manual computation. It provides a simple way to predict interior daylight illumination through skylights and windows. It assumes an empty rectangular room with simple fenestration and shading devices. Since room obstructions can substantially reduce illuminances, especially in sidelit spaces,^{42,43} other methods should be considered in this case (see Chapter 9, Lighting Calculations). The lumen method has been extended to include skylights^{44,45} and sidelit spaces with lightshelves.⁴⁶

The lumen method consists of four basic steps:

1. The exterior illuminances at the window or skylight are determined. These can be calculated as shown in the above section "Daylight Availability."
2. The net transmittance of the fenestration reduces the amount of light that reaches the interior of the room. It includes the transmittance of the glazing, the light loss factor, and other factors that may be required, depending on the sophistication of the fenestration controls used.
3. Coefficients of utilization are ratios of interior to

exterior horizontal illuminances. For the lumen method for toplighting the coefficients provide the average daylight illuminance on the workplane. For the lumen method for sidelighting, coefficients give the illuminance at five predetermined points.

4. The interior illuminance is calculated by taking the product of the factors determined in the first three steps.

The basic equation for the illuminance at a prescribed point using the lumen method is the simple formula

$$E_i = E_x \text{ NT CU} \quad (8-27)$$

where

E_i = interior illuminance in lx,
 E_x = exterior illuminance in lx,
 NT = net transmittance,
 CU = coefficient of utilization.

The procedures for determining the net transmittance and the coefficient of utilization differ for toplighting and sidelighting. If both types of systems are being employed, the illuminance can be computed for each and the illuminances added to give the combined effect.

Lumen Method for Toplighting. For daylighting systems employing horizontal apertures such as skylights at or slightly above roof level, the lumen method for toplighting is used. It is assumed that the skylights are positioned uniformly across the ceiling. The average horizontal illuminance on the workplane is

$$E_i = E_{xh} \tau \text{ CU} \frac{A_s}{A_w} \quad (8-28)$$

where

E_i = average incident illuminance on the workplane from skylights in lx,
 E_{xh} = horizontal exterior illuminance on the skylights in lx,
 A_s = gross projected horizontal area of all the skylights in m^2 ,
 A_w = area of the workplane in m^2 ,
 τ = net transmittance of the skylights and light well, including losses because of solar control devices and maintenance factors,
 CU = coefficient of utilization.

Equation 8-28 can be used to determine the average workplane illuminance if the total skylight area and the horizontal exterior illuminance are known. Conversely, the required skylight area can be determined if the required average workplane illuminance and the horizontal exterior illuminance are known.

The exterior horizontal illuminance is the sum of the illu-

minances from the sun and sky. These are determined using the procedures given in the above section "Daylight Availability."

The net transmittance is determined from a direct transmittance T_D and a diffuse transmittance T_d .⁴⁴ The direct transmittance is used for the sun component and is a function of the angle of incidence. The diffuse transmittance is single valued and is used for the sky component, which is treated as diffuse. Generally, manufacturers provide transmittance data for flat sheets of their glass or plastic in the form of a single value of T_d and a curve showing the variation of T_D with incidence angle.

The net transmittance is also affected by the shape of a skylight, multiple layering, the presence of a skylight well, the presence of louvers or other shades, and light loss factors. Most skylights are domed. This decreases the sheet thickness at the center of the dome, modifying the dome transmittance to

$$T_{DM} = 1.25 T_{FS} (1.18 - 0.416 T_{FS}) \quad (8-29)$$

where

T_{DM} = dome transmittance,
 T_{FS} = flatsheet transmittance.

This does not change the transmittance of the transparent sheet ($T_{FS} = 0.92$) but does increase the transmittance of a translucent sheet ($T_{FS} = 0.44$) by about 25%.

Doming causes the angle of incidence of the direct sunlight to vary over the dome's surface, and increases the light-gathering surface area than a flat sheet. Both these factors may be considered together by noting that the effect of doming is to cause T_D to become constant within 10% for all angles of incidence less than 70° (sun angles greater than 20°).⁴⁴ Thus, for most dome applications a single number for T_D equal to its value at 0° angle of incidence can be used.

To reduce heat gains and heat losses, most contemporary skylights are double domed, most often a transparent dome over a translucent dome. The overall transmittance of such a unit may be obtained from the following equation, which takes into account the interreflections between the two domes:⁴⁷

$$T = \frac{T_1 T_2}{1 - \rho_1 \rho_2} \quad (8-30)$$

where

T_1, T_2 = diffuse transmittances of the individual domes,
 ρ_1 = reflectance from the bottom side of the upper dome,
 ρ_2 = reflectance from the top side of the lower dome.

Reflective losses and interreflections in any light well between the dome and the ceiling plane of the room reduce the net transmittance. This reduction is expressed as a well efficiency N_w , which can be obtained from Figure 8-18 if well

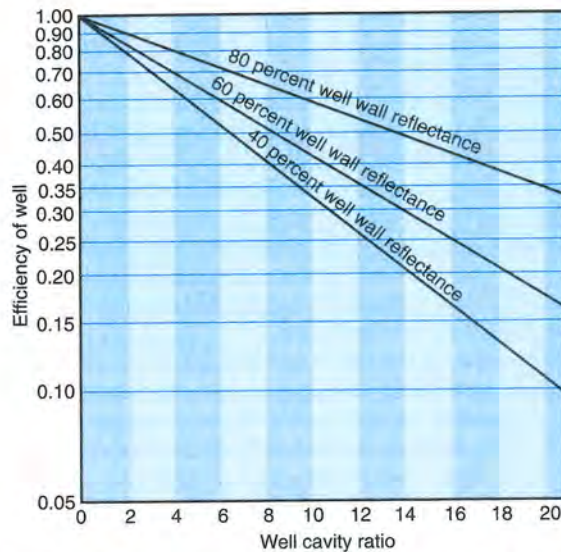


Figure 8-18. Efficiency factors for various depths of light wells, based on well-interreflectance values. See Equation 8-31 for definition of well cavity ratio (WCR).

well reflectance and the well cavity ratio (WCR) are known. The well cavity ratio is given by

$$WCR = \frac{5h(w + l)}{wl} \quad (8-31)$$

where h is the well height, w is the well width, and l is the well length. The dimensions h , w , and l must be expressed in the same units.

The net transmittance should also take into account the ratio of net to gross skylight area (R_a). If any diffusers, lenses, louvers, or other controls are present, their transmittances (T_c) must be included. Finally, the light loss factor (LLF) must be included to take account of dirt depreciation of the skylight and well surfaces. Typical values are given in Figure 8-19. The net transmittances of the skylightwell system are found from

$$\tau_d = T_d N_w R_a T_c \text{LLF} \quad (8-32a)$$

$$\tau_D = T_D N_w R_a T_c \text{LLF} \quad (8-32b)$$

Figure 8-19. Typical Light Loss Factors for Daylighting Design

Locations	Light Loss Factor Glazing Position		
	Vertical	Sloped	Horizontal
Clean Areas	0.9	0.8	0.7
Industrial Areas	0.8	0.7	0.6
Very Dirty Areas	0.7	0.6	0.5

where T_d is equal to the diffuse transmittance and T_D is equal to the direct transmittance of the dome.

Coefficients of utilization (CU) are given in Figure 8-20. These are based on a spacing-to-mounting-height ratio of 1.5:1, a lambertian distribution from the skylight, and a floor reflectance of 0.2. The wall and ceiling reflectances, as well as room cavity ratios (RCR), are required. Room cavity ratios may be obtained from

$$RCR = \frac{5 h_c (l + w)}{lw} \quad (8-33)$$

where h_c is the height from the workplane to the bottom of the skylight well, l is the length of the room, and w is the width of the room. All three parameters must have the same units.

Figure 8-20. Room Coefficients of Utilization for Skylighting (based on a 20% floor reflectance)

Ceiling Reflectance (Percent)	RCR*	Wall Reflectance (Percent)		
		50	30	10
80	0	1.19	1.19	1.19
	1	1.05	1.00	0.97
	2	0.93	0.86	0.81
	3	0.83	0.76	0.70
	4	0.75	0.67	0.60
	5	0.67	0.59	0.53
	6	0.62	0.53	0.47
	7	0.57	0.49	0.43
	8	0.54	0.47	0.41
	9	0.53	0.46	0.41
	10	0.52	0.45	0.40
50	0	1.11	1.11	1.11
	1	0.98	0.95	0.92
	2	0.87	0.83	0.78
	3	0.79	0.73	0.68
	4	0.71	0.64	0.59
	5	0.64	0.57	0.52
	6	0.59	0.52	0.47
	7	0.55	0.48	0.43
	8	0.52	0.46	0.41
	9	0.51	0.45	0.40
	10	0.50	0.44	0.40
20	0	1.04	1.04	1.04
	1	0.92	0.90	0.88
	2	0.83	0.79	0.76
	3	0.75	0.70	0.66
	4	0.68	0.62	0.58
	5	0.61	0.56	0.51
	6	0.57	0.51	0.46
	7	0.53	0.47	0.43
	8	0.51	0.45	0.41
	9	0.50	0.44	0.40
	10	0.49	0.44	0.40

*See Equation 8-33 for definition of room cavity ratio (RCR).

The general lumen method for toplighting (Equation 8-28) can now be applied. For overcast skies, this is

$$E_i = E_{xh \text{ sky}} \tau_d CU N \frac{A}{A_w} \quad (8-34)$$

For a clear or partly cloudy sky, the equation is

$$E_i = (E_{xh \text{ sky}} \tau_d + E_{xh \text{ sun}} \tau_D) CU N \frac{A}{A_w} \quad (8-35)$$

where

- $E_{xh \text{ sky}}$ = exterior horizontal illuminance due to the sky only, in lx,
- $E_{xh \text{ sun}}$ = exterior horizontal illuminance due to the sun only, in lx,
- τ_d = net diffuse transmittance,
- τ_D = net direct transmittance,
- CU = coefficient of utilization,
- N = number of skylights,
- A = area of each skylight in m^2 ,
- A_w = area of the workplane in m^2 .

Note that because the net transmittance depends in part on the well efficiency and the ratio of net to gross skylight area, these factors must be recalculated if the skylight size changes.

Lumen Method for Sidelighting. The prediction of interior daylight illuminance from sidelighting has been simplified by using the standard conditions shown in Figure 8-21. The floor cavity extends from the window sill to the floor and

has a reflectance of 30%. The ceiling cavity extends from the top of the windows to the ceiling and has a reflectance of 70%. The room cavity extends in height (H) from the top of the floor cavity to the bottom of the ceiling cavity, in width (W) along the window wall, and in depth (D) from the window wall to the rear wall; it has a wall reflectance of 50%. The interior daylight illuminance is calculated at five reference points located on a line perpendicular to the window wall across the center of the room at the same height as the window sill. The five points are located along a line at $0.1D$, $0.3D$, $0.5D$, $0.7D$, and $0.9D$.

The procedure described here provides for shades, drapes, solar film, or other simple daylight controls on or at the fenestration. It does not provide for horizontal or vertical window blinds, nor for exterior elements such as sidewalks, streets, other buildings, and overhangs. A more elaborate procedure is available to take account of such elements.

The basic formula used to calculate the horizontal interior daylight illuminance at one of the five reference points is

$$E_i = E_{xv} \tau CU \quad (8-36)$$

where

- E_i = interior horizontal illuminance on a reference point from sidelighting, in lx,
- E_{xv} = exterior vertical illuminance on the window wall in lx,
- τ = net transmittance of the window wall,
- CU = coefficient of utilization.

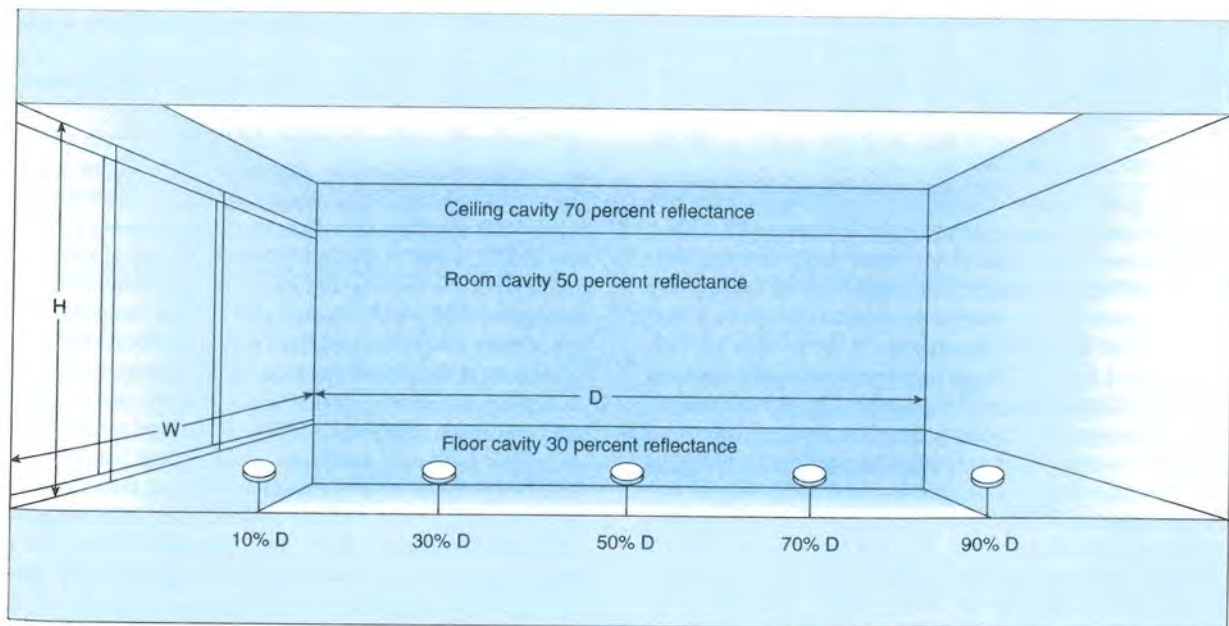


Figure 8-21. Standard conditions in a room for calculating sidelighting. H , W , and D represent room height, width, and depth, respectively.

Superposition is used to obtain the final interior illuminance at a reference point due to multiple sets of daylighting apertures. For instance, the illuminance from the sky and ground are calculated separately and added together to determine the combined effect. The lumen method does account for direct sunlight entering into the room cavity.

The exterior vertical illuminance E_{xv} is the illuminance on the vertical aperture, excluding direct sunlight. For simple exterior situations, that is, with no obstructions, this illuminance is from the sky and ground. That portion due to the sky can be determined using the procedures in the above section "Daylight Availability." The illuminance on the vertical aperture due to the ground can be determined using the method of configuration factors (see Chapter 9, Lighting Calculations), in which exitances and configuration factors are used to calculate the illuminance produced at a point by a large diffuse source. The ground is assumed to be such a source and to exhibit a diffuse exitance, which is given by

$$M_g = \rho_g (E_{xh\ sky} + E_{xh\ sun}) \quad (8-37)$$

where

$$\begin{aligned} M_g &= \text{exitance from the ground in lm/m}^2, \\ \rho_g &= \text{reflectance of the ground,} \\ E_{xh\ sky} &= \text{horizontal illuminance from the sky in lx,} \\ E_{xh\ sun} &= \text{horizontal illuminance from the sun in lx.} \end{aligned}$$

The net transmittance is the product of the transmittance (T) of the glazing; a light loss factor (LLF) representing dirt accumulation; the net-to-gross window area ratio (R_a), representing such elements as mullions and glazing bars; and a factor T_c representing other elements such as shades and drapes which reduce the transmittance of the window. The net transmittance of the window wall is found from

$$\tau = T R_a T_c \text{ LLF} \quad (8-38)$$

The coefficients of utilization (CU) for each of the five reference points in the room are given in Figure 8-22.⁴⁸ If the fenestration is transparent (view-preserving), then the horizontal and vertical exterior illuminances from the half-sky are calculated for the center of the window. Based on a ratio of vertical to horizontal illuminance at the window of 0.75, 1.00, 1.25, 1.50, or 1.75, the coefficients of utilization from Figures 8-22a through 8-22e are used. The ground component coefficient of utilization is given in Figure 8-22f.

If the fenestration is not image preserving, as would be expected from frosted glass, shades, or drapes, then the vertical illuminances from the sky and ground are added. Half of this value is used for both of the sky illuminance and the ground illuminance. Figure 8-22b, based on a uniform sky distribution is used, for the coefficient of utilization of the sky component, and Figure 8-22f is used for the coefficient of utilization of the ground component.

Equations 8-39 and 8-40 below are used to calculate the

illuminance at each of the five reference points in the room. If the window is image preserving, then the illuminances are given by

$$E_i = \tau (E_{xv\ sky} \text{ CU}_{sky} + E_{xv\ g} \text{ CU}_g) \quad (8-39)$$

and for a diffuse window by

$$E_i = 0.5 \tau (E_{xv\ sky} + E_{xv\ g}) (\text{CU}_{sky} + \text{CU}_g) \quad (8-40)$$

where

$$\begin{aligned} E_i &= \text{interior illuminance at a reference point in lx,} \\ \tau &= \text{net transmittance of the window wall,} \\ E_{xv\ sky} &= \text{exterior vertical illuminance from the sky on the window in lx,} \\ \text{CU}_{sky} &= \text{coefficient of utilization from the sky,} \\ E_{xv\ g} &= \text{exterior vertical illuminance from the ground on the window in lx,} \\ \text{CU}_g &= \text{coefficient of utilization from the ground.} \end{aligned}$$

The Daylight Factor Method

The daylight factor method is a low-precision procedure for determining the illuminance at any point in an interior space produced by a sky with a known luminance distribution. Direct sunlight is excluded. The method is generally used with uniform or CIE overcast skies.^{3,49} It is used in northern Europe, where overcast skies predominate, and has some application in North America as well. Daylight factor (DF) is the ratio of the illuminance at a point on a plane, generally the horizontal work plane, produced by the luminous flux received directly or indirectly at that point from a sky whose luminance distribution is known, to the illuminance on a horizontal plane produced by an unobstructed hemisphere of this same sky.

There are three ways in which daylight may reach a point on a horizontal plane within an interior space (Figure 8-23). The sky component (SC) is due to daylight received directly at the point from the sky. The externally reflected component (ERC) is due to daylight received directly at the point from external reflecting surfaces. The internally reflected component (IRC) is due to daylight reaching the point after one or more interreflections from interior surfaces. The daylight factor is the sum of the three components:

$$\text{DF} = \text{SC} + \text{ERC} + \text{IRC} \quad (8-41)$$

In simple interior environments, daylight factor can be determined by hand calculation methods using tables of pre-calculated components for typical geometries. These environments are usually rectangular rooms with a wall of windows. Daylight factors from individual windows can be added to produce the daylight factor due to all the windows. The procedure for determining a daylight factor in such a space is as follows.

Figure 8-22a. Coefficients of Utilization (CU) from Window Without Blinds, Sky Component $E_{xvsky}/E_{xhsky} = 0.75$

Room Depth/Window Height	Percent D*	Window Width/Window Height							Infinite
		.5	1	2	3	4	6	8	
1	10	.824	.864	.870	.873	.875	.879	.880	.883
	30	.547	.711	.777	.789	.793	.798	.799	.801
	50	.355	.526	.635	.659	.666	.669	.670	.672
	70	.243	.386	.505	.538	.548	.544	.545	.547
	90	.185	.304	.418	.451	.464	.444	.446	.447
2	10	.667	.781	.809	.812	.813	.815	.816	.824
	30	.269	.416	.519	.544	.551	.556	.557	.563
	50	.122	.204	.287	.319	.331	.339	.341	.345
	70	.068	.116	.173	.201	.214	.223	.226	.229
	90	.050	.084	.127	.151	.164	.167	.171	.172
3	10	.522	.681	.739	.746	.747	.749	.747	.766
	30	.139	.232	.320	.350	.360	.366	.364	.373
	50	.053	.092	.139	.163	.174	.183	.182	.187
	70	.031	.053	.081	.097	.106	.116	.116	.119
	90	.025	.041	.061	.074	.082	.089	.090	.092
4	10	.405	.576	.658	.670	.673	.675	.674	.707
	30	.075	.134	.197	.224	.235	.243	.243	.255
	50	.028	.050	.078	.094	.104	.112	.114	.119
	70	.018	.031	.048	.059	.065	.073	.074	.078
	90	.016	.026	.040	.048	.053	.059	.061	.064
6	10	.242	.392	.494	.516	.521	.524	.523	.588
	30	.027	.054	.086	.102	.111	.119	.120	.135
	50	.011	.023	.036	.044	.049	.055	.056	.063
	70	.009	.018	.027	.032	.035	.040	.041	.046
	90	.008	.016	.023	.028	.031	.034	.035	.040
8	10	.147	.257	.352	.380	.387	.391	.392	.482
	30	.012	.026	.043	.054	.060	.067	.070	.086
	50	.006	.013	.021	.026	.029	.033	.035	.043
	70	.005	.011	.017	.021	.023	.026	.027	.034
	90	.004	.010	.015	.019	.021	.023	.025	.030
10	10	.092	.168	.248	.275	.284	.290	.291	.395
	30	.006	.014	.026	.032	.036	.041	.044	.059
	50	.003	.008	.014	.017	.019	.022	.024	.032
	70	.003	.007	.012	.014	.016	.018	.019	.026
	90	.003	.006	.011	.013	.015	.016	.017	.024

*Percent D is the relative distance from the window to the opposite wall.

Necessary dimensions are shown in Figure 8-24. A room has a window of width w and height h above the workplane. The point of interest, P , is in the workplane. Portions of the window that lie below the workplane should be neglected. An exterior building has height above the workplane H and is a distance D from the plane of the window.

Sky Component of Daylight Factor. The sky component is due to flux reaching the point directly from the sky through the window. It is the illuminance at the point due to the window, divided by the horizontal illuminance produced by the entire sky. Values have been calculated and tabulated

Figure 8-22b. Coefficients of Utilization (CU) from Window Without Blinds, Sky Component $E_{xvsky}/E_{xhsky} = 1.00$

Room Depth/Window Height	Percent D*	Window Width/Window Height							Infinite
		.5	1	2	3	4	6	8	
1	10	.671	.704	.711	.715	.717	.726	.726	.728
	30	.458	.595	.654	.668	.672	.682	.683	.685
	50	.313	.462	.563	.589	.598	.607	.608	.610
	70	.227	.362	.478	.515	.527	.530	.532	.534
	90	.186	.306	.424	.465	.481	.468	.471	.472
2	10	.545	.636	.658	.660	.661	.665	.666	.672
	30	.239	.367	.459	.484	.491	.499	.501	.506
	50	.121	.203	.286	.320	.335	.348	.351	.355
	70	.074	.128	.192	.226	.243	.259	.264	.267
	90	.058	.101	.156	.188	.207	.215	.221	.223
3	10	.431	.561	.607	.613	.614	.616	.615	.631
	30	.133	.223	.306	.337	.348	.357	.357	.366
	50	.058	.103	.155	.183	.197	.211	.213	.218
	70	.037	.064	.098	.119	.132	.147	.150	.154
	90	.030	.051	.079	.098	.110	.122	.126	.129
4	10	.339	.482	.549	.560	.563	.566	.565	.593
	30	.078	.139	.204	.234	.247	.258	.260	.272
	50	.033	.060	.094	.114	.126	.139	.143	.150
	70	.022	.039	.061	.074	.083	.095	.099	.104
	90	.019	.032	.050	.061	.070	.080	.084	.089
6	10	.211	.343	.433	.453	.458	.461	.461	.518
	30	.033	.065	.103	.123	.135	.145	.148	.167
	50	.015	.029	.047	.057	.064	.073	.077	.086
	70	.011	.021	.033	.040	.045	.051	.054	.060
	90	.010	.019	.028	.034	.038	.044	.046	.052
8	10	.135	.238	.326	.353	.362	.366	.367	.452
	30	.016	.034	.058	.072	.080	.090	.094	.116
	50	.008	.017	.027	.034	.039	.045	.048	.059
	70	.006	.013	.021	.026	.028	.032	.035	.043
	90	.005	.012	.019	.023	.025	.029	.031	.038
10	10	.090	.165	.244	.272	.283	.290	.291	.395
	30	.009	.020	.036	.045	.052	.060	.064	.087
	50	.005	.010	.019	.023	.026	.030	.033	.044
	70	.004	.009	.015	.018	.020	.023	.025	.033
	90	.003	.008	.014	.016	.018	.020	.022	.030

*Percent D is the relative distance from the window to the opposite wall.

for various sky luminance distributions. Figure 8-25³ is such a tabulation for the CIE overcast sky, a window transmittance of 0.85, and point located a distance q perpendicularly away from a lower corner of the window.

The procedure for determining sky component from a window is

1. Determine ratios w_1/q , w_2/q , and h/q , as illustrated in Figure 8-24.
2. For each piece of window, use Figure 8-25 to determine a value of the sky component of the daylight factor.

Figure 8-22c. Coefficients of Utilization (CU) from Window Without Blinds. Sky Component $E_{xvsky}/E_{xhsky} = 1.25$

Room Depth/ Window Height	Percent D*	Window Width/Window Height							Infinite
		.5	1	2	3	4	6	8	
1	10	.578	.607	.614	.619	.621	.633	.634	.635
	30	.405	.525	.580	.594	.599	.612	.614	.615
	50	.287	.423	.519	.547	.556	.569	.571	.573
	70	.218	.347	.461	.501	.515	.522	.525	.526
	90	.186	.307	.428	.473	.491	.483	.486	.487
2	10	.472	.549	.566	.569	.570	.574	.575	.581
	30	.221	.337	.422	.447	.456	.465	.467	.472
	50	.120	.202	.285	.321	.337	.353	.357	.361
	70	.078	.136	.204	.242	.261	.281	.287	.290
	90	.064	.112	.174	.211	.233	.244	.251	.253
3	10	.377	.488	.527	.533	.534	.536	.536	.549
	30	.130	.217	.298	.329	.341	.352	.353	.362
	50	.062	.110	.165	.195	.211	.228	.231	.237
	70	.040	.070	.109	.132	.147	.166	.171	.175
	90	.033	.057	.090	.112	.127	.142	.148	.152
4	10	.300	.424	.484	.494	.497	.499	.499	.524
	30	.080	.143	.209	.240	.255	.267	.269	.283
	50	.036	.066	.104	.126	.140	.156	.160	.168
	70	.024	.043	.068	.083	.094	.109	.115	.120
	90	.021	.036	.056	.070	.080	.092	.099	.103
6	10	.193	.314	.395	.415	.420	.423	.423	.476
	30	.036	.071	.113	.136	.149	.161	.165	.186
	50	.017	.033	.053	.065	.074	.084	.089	.100
	70	.012	.024	.037	.045	.050	.058	.061	.069
	90	.011	.021	.031	.038	.043	.049	.053	.060
8	10	.128	.226	.310	.337	.346	.351	.352	.433
	30	.019	.039	.066	.082	.092	.104	.109	.134
	50	.009	.019	.031	.040	.045	.052	.056	.069
	70	.007	.015	.023	.029	.032	.037	.040	.049
	90	.006	.013	.021	.025	.028	.032	.035	.043
10	10	.088	.164	.241	.270	.282	.290	.291	.396
	30	.011	.024	.043	.054	.062	.071	.076	.103
	50	.005	.012	.022	.026	.030	.035	.038	.052
	70	.004	.010	.017	.020	.023	.026	.028	.038
	90	.004	.009	.016	.018	.020	.023	.025	.034

*Percent D is the relative distance from the window to the opposite wall.

Figure 8-22d. Coefficients of Utilization (CU) from Window Without Blinds. Sky Component $E_{xvsky}/E_{xhsky} = 1.50$

Room Depth/ Window Height	Percent D*	Window Width/Window Height							Infinite
		.5	1	2	3	4	6	8	
1	10	.503	.528	.536	.541	.544	.557	.558	.559
	30	.359	.464	.514	.528	.534	.549	.550	.552
	50	.261	.384	.471	.499	.508	.524	.526	.527
	70	.204	.325	.432	.470	.485	.497	.499	.500
	90	.179	.295	.412	.456	.475	.474	.477	.478
2	10	.412	.477	.490	.492	.493	.498	.499	.505
	30	.201	.304	.379	.402	.410	.422	.424	.429
	50	.115	.192	.269	.304	.320	.339	.343	.347
	70	.078	.136	.204	.241	.261	.286	.292	.295
	90	.066	.117	.183	.221	.246	.262	.271	.273
3	10	.331	.426	.458	.461	.462	.465	.465	.477
	30	.121	.202	.275	.304	.316	.327	.329	.337
	50	.062	.109	.164	.193	.209	.228	.232	.238
	70	.041	.073	.114	.138	.154	.176	.183	.188
	90	.035	.062	.099	.123	.141	.159	.169	.173
4	10	.265	.372	.422	.430	.433	.435	.435	.456
	30	.077	.137	.199	.229	.243	.256	.259	.272
	50	.037	.069	.107	.130	.144	.161	.167	.175
	70	.026	.046	.073	.089	.101	.119	.126	.132
	90	.022	.039	.063	.078	.090	.106	.114	.120
6	10	.173	.281	.351	.368	.373	.375	.375	.422
	30	.037	.073	.115	.137	.151	.164	.168	.189
	50	.018	.036	.058	.071	.080	.092	.098	.110
	70	.013	.026	.040	.049	.056	.064	.069	.078
	90	.012	.023	.035	.043	.048	.057	.062	.070
8	10	.117	.207	.282	.305	.314	.319	.320	.393
	30	.020	.042	.071	.087	.098	.111	.116	.143
	50	.010	.021	.035	.044	.050	.058	.063	.078
	70	.007	.016	.026	.032	.036	.041	.045	.055
	90	.006	.014	.023	.028	.031	.036	.040	.049
10	10	.082	.153	.224	.250	.262	.269	.271	.368
	30	.012	.026	.047	.059	.068	.078	.084	.114
	50	.006	.014	.024	.030	.034	.040	.044	.060
	70	.005	.011	.019	.022	.025	.029	.032	.043
	90	.004	.010	.017	.020	.023	.026	.028	.038

*Percent D is the relative distance from the window to the opposite wall.

3. If point p splits the windows as in Figure 8-24b, then add these two components.
4. If point p is away from the window as in Figure 8-24c, then subtract these two components.
5. If window transmittance is not 0.85, scale the values by the ratio of the actual window transmittance to 0.85.

If an external building obstructs the view of the sky from point p through the window then

6. Determine the ratios $w_1/(q + D)$, $w_2/(q + D)$, and $H/(q + D)$.
7. For each piece of building, use Figure 8-25 to determine a value of obstructed sky component of the daylight factor.
8. If point p splits the building, then add these two components.
9. If point p is away from the building, then subtract these two components.
10. If window transmittance is not 0.85, scale the val-

Figure 8-22e. Coefficients of Utilization (CU) from Window Without Blinds. Sky Component $E_{xvsky}/E_{xhsky} = 1.75$

Room Depth/Window Height	Percent D*	.5	1	2	3	4	6	8	Infinite
1	10	.435	.457	.465	.471	.474	.486	.488	.489
	30	.317	.407	.452	.466	.471	.486	.488	.489
	50	.234	.343	.422	.447	.456	.472	.475	.476
	70	.187	.297	.395	.430	.445	.458	.461	.462
	90	.168	.276	.384	.426	.444	.447	.450	.451
2	10	.357	.412	.422	.424	.424	.430	.431	.436
	30	.180	.271	.335	.356	.363	.375	.378	.381
	50	.106	.177	.246	.278	.293	.313	.318	.321
	70	.074	.130	.194	.229	.249	.274	.282	.284
	90	.065	.116	.181	.219	.244	.264	.273	.276
3	10	.288	.369	.394	.397	.397	.400	.401	.411
	30	.110	.183	.247	.272	.282	.294	.296	.304
	50	.058	.104	.154	.181	.196	.215	.221	.226
	70	.040	.072	.112	.136	.152	.176	.184	.188
	90	.035	.063	.101	.126	.144	.166	.177	.182
4	10	.232	.324	.365	.371	.373	.375	.375	.394
	30	.071	.127	.183	.209	.222	.235	.238	.250
	50	.036	.067	.104	.125	.139	.157	.163	.171
	70	.025	.046	.072	.089	.101	.119	.127	.134
	90	.022	.041	.065	.082	.095	.114	.124	.130
6	10	.153	.247	.307	.320	.324	.326	.327	.367
	30	.035	.070	.109	.130	.143	.155	.160	.180
	50	.018	.036	.058	.071	.080	.091	.098	.110
	70	.013	.026	.041	.051	.058	.067	.073	.082
	90	.012	.023	.037	.046	.052	.062	.069	.078
8	10	.104	.184	.249	.269	.276	.281	.282	.346
	30	.020	.042	.070	.086	.096	.109	.115	.141
	50	.010	.022	.036	.046	.052	.060	.066	.081
	70	.008	.017	.027	.033	.038	.044	.048	.059
	90	.007	.015	.024	.030	.034	.040	.044	.054
10	10	.074	.138	.201	.223	.233	.240	.242	.328
	30	.012	.027	.048	.059	.067	.078	.084	.114
	50	.006	.014	.026	.032	.036	.043	.047	.064
	70	.005	.011	.020	.024	.027	.031	.034	.046
	90	.004	.010	.018	.022	.024	.028	.031	.042

*Percent D is the relative distance from the window to the opposite wall.

ues by the ratio of the actual window transmittance to 0.85.

11. Subtract the result obtained from the unobstructed window.

Externally Reflected Component of Daylight Factor.

The externally reflected component is generally small and is usually roughly approximated. To obtain its value for the CIE overcast sky, the obstructed sky component (obtained in steps 6 to 10 above) is multiplied by 0.2 if it is less than 20, or by 0.1 if it is greater than 20.

Figure 8-22f. Coefficients of Utilization (CU) from Window Without Blinds (Ground Component)

Room Infinite Depth/ Window Height	Percent D*	Window Width/Window Height							
		.5	1	2	3	4	6	8	
1	10	.105	.137	.177	.197	.207	.208	.210	.211
	30	.116	.157	.203	.225	.235	.241	.243	.244
	50	.110	.165	.217	.241	.252	.267	.269	.270
	70	.101	.162	.217	.243	.253	.283	.285	.286
	90	.091	.146	.199	.230	.239	.290	.292	.293
2	10	.095	.124	.160	.178	.186	.186	.189	.191
	30	.082	.132	.179	.201	.212	.219	.222	.225
	50	.062	.113	.165	.189	.202	.214	.218	.220
	70	.051	.093	.141	.165	.179	.194	.198	.200
	90	.045	.079	.118	.140	.153	.179	.183	.185
3	10	.088	.120	.157	.175	.183	.185	.163	.167
	30	.059	.107	.154	.176	.187	.198	.193	.198
	50	.039	.074	.114	.134	.146	.157	.166	.170
	70	.031	.055	.085	.101	.111	.122	.127	.130
	90	.028	.047	.070	.083	.092	.107	.113	.115
4	10	.073	.113	.154	.174	.183	.187	.176	.184
	30	.040	.082	.127	.148	.159	.170	.177	.185
	50	.025	.049	.078	.094	.103	.113	.117	.123
	70	.020	.036	.054	.065	.071	.079	.083	.087
	90	.019	.032	.046	.054	.060	.069	.073	.076
6	10	.056	.106	.143	.164	.175	.184	.173	.194
	30	.021	.050	.081	.098	.107	.117	.123	.138
	50	.013	.027	.041	.049	.054	.060	.064	.072
	70	.011	.021	.029	.033	.035	.039	.041	.046
	90	.011	.020	.026	.030	.032	.035	.037	.042
8	10	.036	.082	.122	.143	.156	.166	.170	.208
	30	.011	.029	.050	.062	.070	.078	.082	.101
	50	.007	.016	.024	.028	.031	.035	.038	.046
	70	.006	.013	.018	.020	.021	.023	.025	.030
	90	.006	.013	.017	.019	.020	.022	.023	.028
10	10	.024	.061	.109	.120	.131	.144	.147	.200
	30	.006	.017	.034	.040	.046	.053	.056	.076
	50	.004	.010	.016	.018	.020	.023	.024	.033
	70	.004	.009	.013	.014	.015	.016	.016	.022
	90	.004	.009	.013	.013	.014	.015	.016	.021

*Percent D is the relative distance from the window to the opposite wall.

Internally Reflected Component of Daylight Factor. The procedure for obtaining the internally reflected component is based on the theory of the integrating sphere and the concept of split flux, namely that the internally reflected flux reaching the point in question is composed of two parts, a component reflected first from the room cavity above the workplane and a second component reflected first from the floor cavity.

Values of minimum internally reflected component of daylight factor can be tabulated for various room sizes, sur-

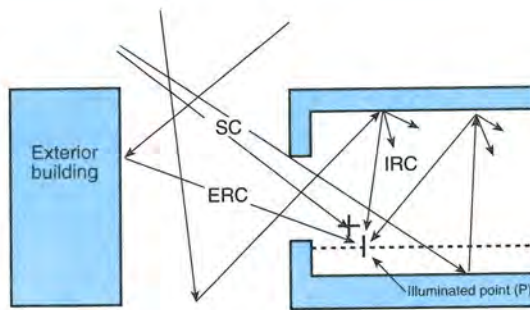


Figure 8-23. Daylight factor components. See Equation 8-41.

face reflectances, and amount of window area. Values for a room of 36 m² (390 ft²) floor area, 3 m (10 ft) ceiling height, and 70% ceiling reflectance are shown in Figure 8-26. With a precision appropriate for the daylight factor method, these values of minimum internally reflected component can be modified for different floor areas and wall reflectances, different ceiling reflectances, and average internally reflected component.

Figure 8-27a shows the multipliers to convert values of minimum internally reflected daylight factor from Figure 8-26 for other floor areas and wall reflectances. Figure 8-27b

shows the multipliers to convert for different ceiling reflectances. Figure 8-27c gives the multipliers to convert minimum internally reflected daylight factors to average internally reflected daylight factors.

Approximate Average Daylight Factor. Very often the average daylight factor on a horizontal reference plane, usually the work plane, is desired. This can be obtained from the following empirical expression:

$$ADF \cong \frac{\tau A_g \theta}{A_s (1 - \rho^2)} \quad (8-42)$$

where

ADF = average daylight factor, in percent,

τ = the decimal transmittance of the glazing,

A_g = the net glazing area,

A_s = the total interior surface area, including windows, in the same units as A_g ,

ρ = is the area-weighted average reflectance of all interior room surfaces, including windows,

θ = the angle in degrees in the vertical plane subtended by the portion of the sky that is visible from the center of the window.

Experience has shown that when ADF is 5% or greater, an interior space will appear to be well lighted. When the ADF is less than 2%, the interior space will seem dimly lighted.

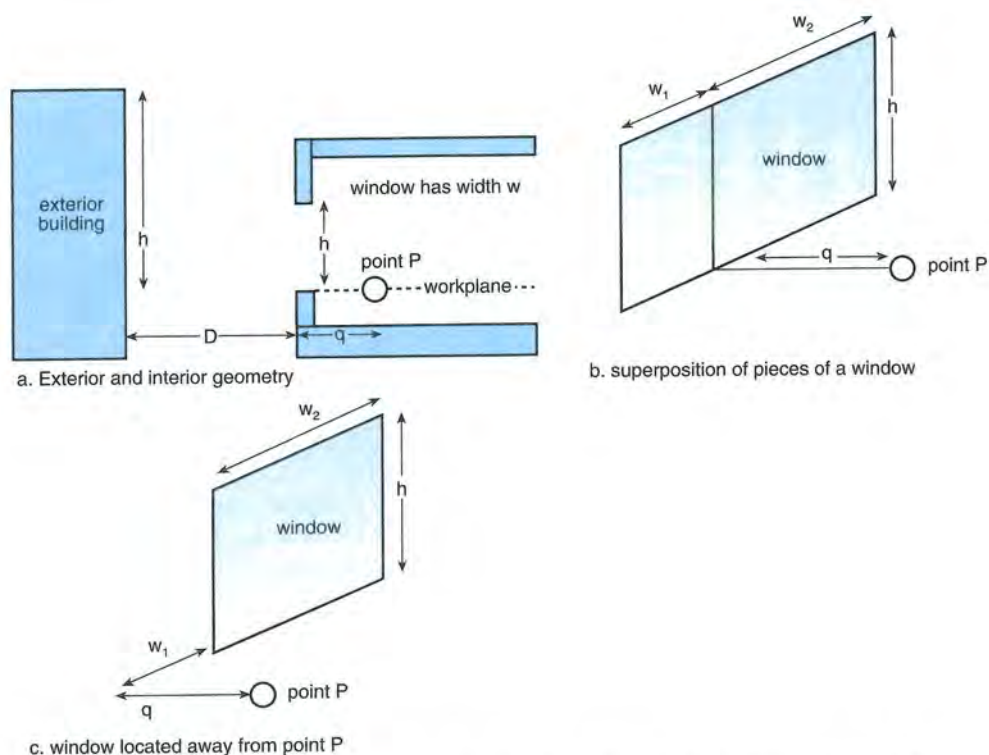


Figure 8-24. Geometry for determining daylight factor in a simple environment. See text.

Figure 8-25. Sky Components of Daylight Factor, in Percent, for CIE Overcast Sky

h/q*	w/q*											
	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.5	2.0	3.0	6.0
5.0	1.3	2.5	3.7	4.9	5.9	6.9	8.4	9.6	11.9	13.0	14.2	14.9
3.0	1.2	2.4	3.7	4.8	5.9	6.8	8.3	9.4	11.4	12.7	13.7	14.1
2.0	1.2	2.3	3.5	4.5	5.5	6.4	7.8	8.7	10.4	11.7	12.4	12.6
1.8	1.0	2.0	3.1	4.0	4.8	5.6	6.7	7.5	8.9	9.7	10.0	10.2
1.6	0.97	1.9	2.9	3.8	4.6	5.3	6.3	7.1	8.3	9.0	9.3	9.5
1.4	0.90	1.8	2.7	3.5	4.2	4.9	5.8	6.5	7.6	8.2	8.5	8.6
1.2	0.82	1.6	2.4	3.2	3.8	4.4	5.2	5.9	6.8	7.3	7.5	7.6
1.0	0.71	1.4	2.1	2.7	3.3	3.8	4.5	5.0	5.8	6.1	6.2	6.3
0.9	0.57	1.1	1.7	2.2	2.6	3.0	3.6	4.0	4.5	4.7	4.8	5.0
0.8	0.50	0.99	1.5	1.9	2.2	2.6	3.1	3.4	3.8	4.0	4.1	4.2
0.7	0.42	0.83	1.2	1.6	1.9	2.2	2.6	2.9	3.2	3.3	3.4	3.4
0.6	0.33	0.68	0.97	1.3	1.5	1.7	2.1	2.3	2.5	2.6	2.7	2.8
0.5	0.24	0.53	0.74	0.98	1.2	1.3	1.6	1.8	1.9	2.0	2.1	2.1
0.4	0.16	0.39	0.52	0.70	0.82	0.97	1.1	1.2	1.4	1.5	1.5	1.5
0.3	0.10	0.25	0.34	0.45	0.54	0.62	0.75	0.89	0.95	0.96	0.97	0.98
0.2	0.06	0.14	0.18	0.26	0.30	0.34	0.42	0.47	0.50	0.51	0.52	0.53
0.1	0.03	0.06	0.09	0.11	0.12	0.14	0.20	0.21	0.22	0.23	0.23	0.24
0.1	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08

*See Figure 8-24 for terms h, w, and q.

The ADF is a suitable metric for shallow side-lighted rooms and for rooms lighted by skylights. It is not a valid metric for deep side-lighted rooms because of the effect of the exponential decay of daylighting as distance from the window increases. Limiting room is 3 to 4 window heights above the work plane.

Comparison and Accuracy of Methods

The utility of computational methods for daylighting depends on the information required, the complexity of the daylighting system, and the stage in the design process at

which computations are being performed. Methods that give average illuminance for typical sky conditions can be useful early in the design process when alternative strategies are being evaluated. The relative simplicity of these methods can not only help make clear what the lighting will be like in the space but also reveal changes to the design that yield improvement.

Later in the design process, detailed calculations are often necessary to verify illuminances at points and luminance ratios. In this case, insight into how the design functions is not revealed by the computational method itself but by the results it gives, that is, illuminances and luminances. The

Figure 8-26. Minimum Internally Reflected Components of Daylight Factor, in Percent

Ratio of Window to Floor Area	Floor Reflectance (%)											
	20				30				40			
	Wall Reflectance (%)				Wall Reflectance (%)				Wall Reflectance (%)			
	20	40	60	80	20	40	60	80	20	40	60	80
.02	—	—	0.1	0.2	—	0.1	0.1	0.2	—	0.1	0.2	0.2
.05	0.1	0.1	0.2	0.4	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6
.07	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6	0.2	0.3	0.6	0.8
.10	0.1	0.2	0.4	0.7	0.2	0.3	0.6	0.9	0.3	0.5	0.8	1.2
.15	0.2	0.4	0.6	1.0	0.2	0.5	0.8	1.3	0.4	0.7	1.1	1.7
.20	0.2	0.5	0.8	1.4	0.3	0.6	1.1	1.7	0.5	0.9	1.5	2.3
.25	0.3	0.6	1.0	1.7	0.4	0.8	1.3	2.0	0.6	1.1	1.8	2.8
.30	0.3	0.7	1.2	2.0	0.5	0.9	1.5	2.4	0.8	1.3	2.1	3.3
.35	0.4	0.8	1.4	2.3	0.5	1.0	1.8	2.8	0.9	1.5	2.4	3.8
.40	0.5	0.9	1.6	2.6	0.6	1.2	2.0	3.1	1.0	1.7	2.7	4.2
.45	0.5	1.0	1.8	2.9	0.7	1.3	2.2	3.4	1.2	1.9	3.0	4.6
.50	0.6	1.1	1.9	3.1	0.8	1.4	2.3	3.7	1.3	2.1	3.2	4.9

Figure 8-27. Multipliers for Minimum Internally Reflected Daylight Factor

a. Different Floor Areas and Wall Reflectances				
Floor Area m ² (ft ²)	Wall Reflectance (%)			
	20	40	60	80
	Multiplier			
10 (108)	0.6	0.7	0.8	0.9
36 (388)	1.0	1.0	1.0	1.0
100 (1080)	1.4	1.2	1.0	0.9

b. Different Ceiling Reflectances		c. From Minimum to Average IRC	
Ceiling Reflectance (%)	Multiplier	Wall Reflectance (%)	Multiplier
40	0.7	20	1.8
50	0.8	40	1.4
60	0.9	60	1.3
70	1.0	80	1.2
80	1.1		

most complex methods are required to produce computer visualizations of daylighted spaces.

The accuracy of these computational methods depends on the nature and extent of the assumptions they make, and on the accuracy of the data used. Predicting absolute levels of illuminance in daylighted interiors is difficult and often unnecessary, since the amount of light getting into a building will depend on the availability of daylight; often the ratios are what is important. Reasonable accuracy in the ratio between interior levels and exterior availability can be expected from most physical models and computational models. Ten percent is achievable in a carefully made physical model or an accurate computer model based on physical principles and an accurate description of the geometry of the space.

DESIGN METHODS AND EVALUATION TECHNIQUES⁵⁰⁻⁵²

Daylighting designs may be evaluated throughout the design stages by manual methods, scale model photometry, and computer simulation.

Shading Mask and Sun Path Diagram

A shading mask, when combined with a sun path diagram, can be used to determine several important metrics of daylighting efficacy, including hourly and annual solar exposure of fenestration; degree of shading provided by trees; effects of overhangs, fins, or other architectural features; and solar penetration. Successful construction of a shading mask de-

pends on an accurate determination of the relevant profile angle. The Libby-Owens-Ford Sun Angle Calculator⁵³ is a convenient manual tool for determining profile angles for a wide range of northern latitudes.

Instructions for constructing and using shading masks can be found in Moore⁵⁴ and Olgyay and Olgyay.⁵⁵ Computer software simulation and architectural rendering programs that offer daylighting computations⁵⁶ also can be used to show the amount of shading and direct sun penetration for particular dates and times.

Scale Model Photometry^{57,58}

Scale-model and full-scale photometry allow the investigation of spaces and fenestration systems that are more complex than can be evaluated using lumen methods or currently available computer programs. Scale models provide a simple means of changing one variable at a time (e.g., window geometry, shading system, surface reflectance), allowing the designer to select optimum conditions to integrate the natural and electric lighting systems. Smaller models ($\frac{1}{4}$ in. = 1 ft and smaller) are used to evaluate exterior shading, building massing, and siting issues. Larger scales ($\frac{3}{8}$ in. = 1 ft and larger) are required for interior evaluations and quantitative measurements.

The performance of most models is evaluated under both clear and overcast sky conditions. Artificial sunlight is created with a nearly parallel beam electric light source. The variation in solar angles can be reproduced either by moving the "sun" in an arc around the model or by inclining the model on a tilting heliodon table. For quantitative sun studies, the CIE standard clear-sky component also must be simulated. If the clear-sky component is not represented, the sun study is limited to qualitative evaluations of shading angles, sunlight penetration, and glare, which are usually documented visually, photographically, or on video.

The overcast sky condition is simulated by reproducing the luminance distribution of the CIE standard overcast sky inside a model testing room. The daylighting model is placed inside the room and illuminance measurements are taken with a series of photocells at selected locations inside the model. The photocells are usually connected to a lighting logger or computer. The measurements are used to generate interior daylight illuminance contours and to estimate potential electric lighting energy savings from daylighting control systems.

However, photometry requires the use of special-purpose equipment, and illuminances can be determined only for the sky conditions under which measurements are made. They may not be representative of average conditions, because instantaneous sky conditions can vary considerably from long-term averages. The measured sky conditions can be compared with daylight availability measurements, as discussed below. In making this comparison, it is desirable to obtain measurements for a range of sky conditions (that is, overcast and clear) and, in the case of clear skies, for a range of sun

positions (for example, at 4-min intervals from 8 a.m. to 8 p.m., 4 min being the interval in which the sun changes position by 1°). Measurements under overcast skies are discussed in Reference 49.

Considerations in Using Photometric Instruments

Because of the short-term variability of daylight, it is usually necessary to use sensors connected to a data logger with recording capability. An alternative is the use of artificial skies and suns, although only a few such facilities exist, mostly at universities or research institutions. Artificial skies and suns also have limitations.⁵⁰

Some factors contributing to error in scale model photometry^{50,58} are substantially under the control of the user, including relative calibration of sensors, surface reflectances, and the fidelity with which the model replicates the space and fenestration of interest (although this can become quite difficult with complex fenestration systems). Other factors to consider are listed below.

Photocell Leveling. At the rear of deep sidelighted spaces, where much of the light striking a photocell does so at an oblique angle, small errors in leveling a photocell may produce large errors in illuminance measurements; for an incidence angle of 85°, a sensor misalignment of 2° will result in an error of 40% for the sky component.⁵⁹

Photocell Size. A given sensor has a different view of the sky in a model than in a fullscale space. Where illuminances are changing rapidly and by large amounts (for example, close to a window without shading controls), significant error may result.

Sensor Placement. While it is not difficult to place photocell faces with sufficient accuracy for most conditions, small placement errors in models result in large errors where flux gradients are steep.

Effects of Space Contents. Space contents, such as sensor holders in scale models, may increase internal reflections and lead to significant overestimates. Such holders should be painted matte black unless their luminous characteristics correspond to features that would exist in the proposed design.

Luminance-based measurements using calibrated video cameras can record thousands of luminance measurements in a physical model,⁴⁰ allowing evaluation of lighting attributes such as luminance distribution, color, and visual performance. These videobased systems can also assist the designer in recording subjective evaluations of the model.

Measurement of Sky Conditions

It is generally necessary to make measurements of the total illuminance on an unobstructed horizontal surface (the global illuminance) simultaneously with interior measurements as

a record of daylight availability. Other important measures are the diffuse illuminance on an unobstructed horizontal surface and the zenith luminance. The most basic means of determining the diffuse illuminance is screening a sensor with a shadow band and using a correction factor to compensate for the diffuse daylight obstructed by the shadow band.⁶⁰ It may also be useful to record daylight on vertical planes of interest, usually facing one or more of the cardinal directions, which necessitates the use of screening devices to cut off ground-reflected light.⁶¹

Computer Simulation

Computer-based simulation methods for daylighting evaluation offer flexibility that scale-model photometry and manual methods sometimes cannot. They are especially valuable when the complexity of the building would make a scale model too costly to construct or when there is the need to evaluate a variety of glazing options. Computer-based simulations provide a convenient means of parametrically evaluating designs in comparison to other design alternatives. Computer programs are readily available for common computer hardware. They can calculate workplace illuminance, daylight factors, surface luminance, a variety of glare and illumination quality, and performance metrics, and often can produce realistic color renderings.³⁶⁻³⁸ The procedures used in these programs are described in the section "Computer Calculations."

Analysis of sunlight penetration and fixed shading can be carried out with many CAD programs that provide shadowcasting as part of their rendering features. For calculation of illuminances, dedicated lighting software with daylighting capability is available.³⁶⁻³⁸

DAYLIGHTING DESIGN CONSIDERATIONS⁶²

Developing Goals

The earlier in the design process that daylighting is considered as a fundamental, form-giving component of building design,⁶³ the greater the building benefits from the use of daylighting features.^{64,65}

The most successfully implemented daylighting design involves broad agreement among all design disciplines as the goals and features of the building are developed. The provisions for daylighting are affected by decisions pertaining to many other building parameters. For example, the installation of dimmable lighting control systems may provide only minimal savings if heavily tinted glazing, specified to control heat gain and glare, excessively reduces the admission of all daylight, even if there is no direct sun.

Daylight apertures serve two distinct purposes: allowing views to the exterior and providing functional ambient light

for the interior. Frequently the design considerations for these functions conflict. For example, view windows occur low in the wall at eye height, while functional daylight apertures distribute light most evenly when they are placed high in the wall. It is important to identify the role and function each aperture is intended to perform, which may require providing separate apertures for view and daylighting.

Daylight Penetration and Glare Control

Glare control is a major consideration in daylighting because of the intensity of the source (especially in the case of direct sunlight) and because, in many situations, achieving spatially balanced illumination is difficult with a source that is unevenly distributed through the space (for example, sidelighting of deep-plan buildings). A rule of thumb is that the distance of useful daylight penetration with sidelighting is usually not more than twice the window head height. Room furnishings in particular may drastically reduce daylight penetration in sidelighted spaces.^{42,43}

Advanced daylighting designs manipulate the daylight entering the space to carefully control the distribution of light and the balance of surface luminances under a variety of sun angles and sky conditions. The effects of daylight on the luminance and illuminance ratios in a space can be studied with daylight models, computer simulations, and full-scale mockups.

Control of Glare from Direct Sunlight. Designs should be developed such that direct sunlight is, or can be, excluded from critical task areas. Sources of direct specular reflection should also be identified and eliminated, or their reflectances reduced as much as possible. An exception is if the reflecting surface is used as part of a daylight harvesting feature such as a lightshelf. In this case, care should be taken to ensure that the reflected sunlight is sufficiently diffused and strikes surfaces that are not in the direct line of sight of building occupants.

Control of Glare from Diffuse Skylight. Glare increases substantially with larger views of the upper portions of the sky. This can be avoided by limiting the height of the view window head in critical task areas, by screening upper window areas from view, or by placing daylighting apertures high enough to be out of the normal field of vision. The task also may be arranged so that the user does not face the window, although this may conflict with user view preferences. Glare can also be reduced by using light colors on interior surfaces, especially near windows, to reduce luminance ratios.

Evaluation of Designs⁶⁶

A logical sequence in evaluating a proposed design is the following:

1. Evaluate the balance of luminances and illuminance levels through the space. Surface luminance

balances (or imbalances) and illuminance levels are major factors in lighting quality and mood, task performance, and associated comfort.

2. Determine whether sunlight will fall on any areas where it should be excluded, and address any resulting problems by changing the daylighting apertures or providing fixed or movable controls.
3. Determine whether sky glare will be a problem, and either make adjustments to the design to control glare or provide fixed or movable controls.
4. Evaluate the performance of the daylighting system acting in concert with the electric lighting, using illuminance, luminance, and energy use as metrics. Assess the pattern of sunlight in spaces where it is being provided as an amenity.

For a minimum investigation at the conceptual stage, daylighting should be evaluated with solar altitudes corresponding to the solstices, around December 21 and June 21, and one equinox, around March 21 or September 22. A range of sky conditions should be tested, including, at least, the extremes for a particular orientation, such as solar noon and the earliest and darkest hours when daylighting occurs for a south-facing facade.

It is important that designs be checked for critical conditions when sunlight may enter spaces. For instance, at northern latitudes, direct sunlight may strike the north-facing facades of buildings on summer evenings. In the winter, the sun will be low in the sky, resulting in deep penetration of shading systems and sidelighted spaces. Nearer the equator, the high midday summer sun can more readily enter spaces through skylights.

Assessment of Daylighting Effects on Energy Use

Daylighting apertures can have either a positive or negative impact on the overall building energy performance. Direct solar gains into the building interior can require additional cooling, whereas electric lighting load reductions can have a direct electricity cost savings as well as an indirect reduction in cooling loads. A well-designed daylighted building can provide significant improvement in overall building energy performance when these impacts are balanced for the building type, use, and location.

Use of daylight in buildings can reduce the need for electric lighting during the day while maintaining sufficient illuminance levels. Because the IR heat component of daylight can be excluded from the building with spectrally selective, low-emissivity glazing and low U-value glazing assemblies, the result is a building that places a lower demand upon the cooling system. In heating-dominated climates daylighting permits the maximum benefit from passive solar heating and can shift heating costs from electrical sources to more economical gas sources. The Illuminating Engineering Society of North America (IESNA) and the American Society of

Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) have produced an energy-efficient design guide,⁶⁷ which provides procedures for estimating the contribution of daylighting to energy conservation.

Integration of Daylight and Electric Lighting

The integration of daylight and electric light begins with an understanding of the overall intention of the lighting design. The designer must decide what roles daylight and electric lighting will play in meeting the lighting objectives. Daylight's contribution across the space at different times of the day and year must be determined. This may include evaluating daylight surface luminance ratios, illuminance levels and contours, daylight zones, temporal variations in daylight availability (direction and intensity), and how daylight distribution changes with adjustable shading and fenestration elements.

The electric lighting may be designed to contrast with the daylight, as in an atrium that dramatically changes moods as it goes from a predominantly daylighted, daytime ambience to a predominantly electrically lighted nighttime scene. In many daylighted buildings, however, the two components are designed to work together in a task/ambient approach, where daylight provides the ambient lighting (supplemented by electric light as necessary) and electric light provides the task and accent lighting. In this case, the ambient electric lighting system is designed to reduce daylight gradients and to balance luminances in the space. The ambient electric lighting must be circuited and zoned to follow the daylight zones. This is accomplished by aligning the electric lighting circuits parallel to the daylight contours. Ideally, the ambient electric light is delivered to the same surfaces as the daylight so that the transition between daylight and electric light is smooth.

Electric Lighting Control

If ambient electric lighting has been designed to correspond with daylight zones, an automatic control system can be implemented to turn off or dim the electric lights in response to daylight availability. Automatic control is accomplished by a photocell that evaluates the light level and sends a signal to a control unit to dim or switch the electric lights to maintain a preset target level. Automatic control provides more predictable performance than manual control, but control zones must be sufficiently small and matched well with daylight availability to achieve light level consistency.

For sidelighting, the photocell usually is placed on the ceiling looking down at a representative task area; for skylighting, it is frequently placed in a skylight looking up at the available daylight. Switching of electric lighting in response to daylight produces abrupt changes in the light level when the switching occurs. This can be reduced by using multiple switching steps. Dimming is more expensive, but it is also more gradual and acceptable to building occupants.

Commissioning

In order for a well-designed daylighting system to provide the benefits expected by owners and occupants over time, the system should be commissioned after installation. Commissioning can be defined as a systematic process that ensures that all elements of the daylighting system perform interactively and continuously according to documented design intent and the needs of the building owner. Most daylighting systems consist of a fenestration element, typically with some operational elements to modulate daylight and glare, and an electric lighting control system, which may consist of a sensor, a controller, and a dimming ballast. At a minimum, commissioning implies verification that the proper equipment was installed in a manner that meets documented installation requirements. In this context, commissioning could be completed by the general contractor. However, commissioning more typically includes calibration of any electrical or mechanical sensors such that they produce the desired control signal to the system under the specific conditions of the room design and over a wide range of incident daylighting conditions. This often requires special skills and equipment, such as a photometer to set proper light levels.

Experience to date⁶⁸ suggests that commissioning of daylighting systems is commonly ignored and, when it is done, is often fraught with technical and procedural difficulties. Commissioning criteria should be specified by the designer and/or provided by the manufacturer. In most cases, commissioning activities should be carried out in spaces that are furnished and ready for occupancy. Commissioning must be completed for each unique physical zone or control system zone and for each building orientation.

Operationally it is useful to think about the daylighting system in two elements: fenestration controls and lighting controls. Commissioning of fenestration controls can be divided into three cases, each with its own specific requirements and procedures: 1) systems with fixed elements that may need adjustment after installation, such as some lightshelves; 2) systems with manually operated controls, such as interior venetian blinds, and 3) systems with automated controls, such as exterior motorized louvers. Once the performance of the fenestration systems is verified, the lighting control system can be commissioned. The placement and orientation of the photosensor must be verified for optimum operation. The light sensor and controller must be adjusted to provide the desired light level at the task location. The specifics of this procedure vary with control system type (open versus closed loop control) and hardware selection.⁶⁹

DAYLIGHTING SYSTEMS

Fenestration and Building Sections^{3,63,70-75}

Unilateral Sidelighting. This design (Figure 8-28a) lends itself to continuous fenestration and curtain wall construc-

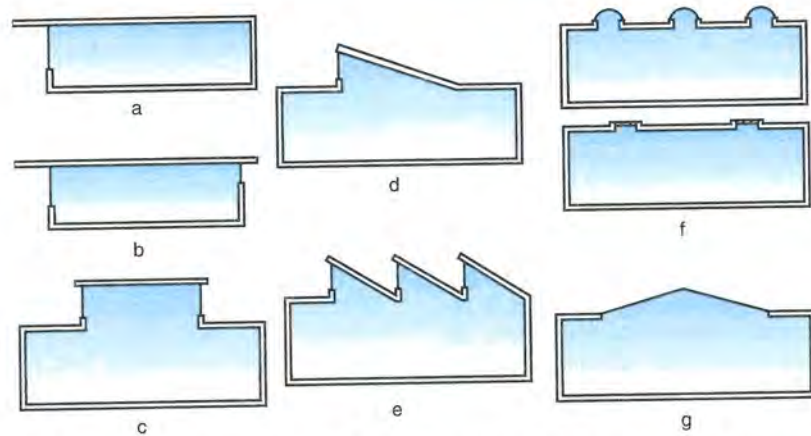


Figure 8-28. a. Unilateral lighting section. b. Bilateral lighting section. c. Roof monitor lighting section. d. Clerestory lighting section. e. Sawtooth lighting section. f. Skylight sections. g. Atrium section.

tion. To avoid large ranges in daylight illuminances (greater than 25:1), the distance from the window wall to the inner wall should normally be limited to twice the window head height with clear glazing. For this reason, window heads are often placed close to the ceiling, although the resulting increase in the view of the sky also increases glare. Deeper spaces may be created if additional lighting opposite the window wall is used to balance illuminances.

Window with Overhang. Overhangs (Figures 8-28a and b) may be used to reduce sunlight penetration in latitudes where the sun is high in the sky during the times that spaces are occupied. This reduces the view of the upper portion of the sky and provides a less drastic range of illuminances across a space. However, overhangs also reduce daylight penetration, although this may be offset to some degree by the redirection of ground-reflected light into the space.

Window with Blinds. Venetian blinds can be effective in controlling the entry of sunlight, reducing sky glare, and redirecting light to the ceiling. They can provide a shading effect equivalent to a very substantial overhang. Building occupants claim to enjoy the control offered by blinds, but they tend to adjust blinds infrequently.

Split Window with Upper and Lower Blinds. This allows for different adjustments for the upper and lower portions of the glazing. For instance, daylight can still be admitted deep into the space when the lower blinds are closed to exclude sunlight from a task area.

Split Window with Low-Transmittance Upper Panel. This reduces glare from the upper portion of the sky while not distorting the view of the ground plane.

Window with Vertical Shading Elements. Devices such as fins are effective sun controls on east and west walls. Combinations of vertical and horizontal elements (for exam-

ple, egg crate shades) as sun controls are common in southern latitudes.

Window with Light Shelf. Light shelves are fixed exterior and interior shading systems used in combination with glazing placed above the lower glazing used for viewing in sidelighting systems. By screening the upper portion of the sky, they allow the use of higher window heads, providing deeper and more uniform daylighting while eliminating the glare that would normally accompany the use of tall windows.

Bilateral. Bilateral daylighting (Figure 8-28b) balances the admission of light. This system permits doubling of the room width receiving light that is possible with unilateral daylighting. The second set of windows often occupies only the upper part of the wall. At least one set of windows is exposed to the sun, necessitating glare control. Sloped ceilings, sometimes employed with this design, have little effect on the quantity or quality of illumination except where they can allow a higher window head.

Roof Monitor. This daylighting system is most frequently used in industrial buildings where a central high bay is set between two lower flanking areas (Figure 8-28c). High-reflectance roof surfaces below the monitors increase interior illuminances.

Clerestory. Additional windows on the roof, facing the same direction as the main side-lighting window, aid in overcoming the daylighting penetration limitations of the unilateral section (Figure 8-28d).

Staggered Building Sections. Staggered building sections can allow for deep penetration of daylight along with greater flexibility in the layout of spaces. They are a variation on combinations of clerestory lighting and other sidelighting systems.

Sawtooth. This fenestration (Figure 8-28e) is used principally in large industrial buildings. Slanting the windows to face the sky increases the potential daylighting contribution, but this may be offset by increased dirt collection on the glazing. Heat gain may also increase.

Skylights. Skylights assume many forms, including domes, panels with integral sun and luminance control, panels of fiber-glass-reinforced plastic, and louvers for heat and glare control. Skylight detailing requires special attention to prevent moisture penetration and dripping due to condensation. Operable skylights may also provide ventilation and cooling (Figure 8-28f).^{51,76} The use of skylight wells, splayed at about 60° and matte-white finished, is essential if a uniform, glare-free daylight distribution is to be achieved.

Atria.^{77,78} These are large-area daylighting sources that have several forms, such as ridge-type (Figure 8-28g), sheds, pyramids, and domes. Because of the large area, lower-range (10 to 25%) light transmissions are used. Translucent sandwich panels with highly diffusing glass fiber-reinforced polymer faces are especially suitable for diffuse shadow-free daylighting, even under direct sun conditions. These panels provide excellent control of light and heat.

Solar Lighting Systems. Solar lighting systems include systems of reflectors or other optical elements intended for steering or redirecting direct solar flux with relatively minor contributions from diffuse sky light. Tubular skylights are representative of such systems, as are a variety of additional schemes including mirrored louvers in clerestory windows, mirrored louvers in otherwise conventional skylights, and more complex systems using sun-tracking, concentrating, and piping subsystems.⁷⁹

Material and Control Elements

A variety of materials are used in daylighting systems. Transmittance data for several of these materials are provided in Figure 8-29. It should be noted that the transmittance of materials is a function of the incident angle of the light.

Transparent (High-Transmittance) Materials. These transmit light without appreciably changing its direction or color; they are image preserving. Common types are sheet, polished plate, and float and molded glass, as well as some rigid plastic materials and formed panels.

Transparent (Low-Transmittance) Materials. Low-transmittance (gray) glasses and plastics offer luminance reduction that increases as their transmittance decreases. During daylight hours, the ability to view into a room is reduced. At night, the view into a room is apparent while the view from a room to the outdoors is reduced. Lower transmittances, below 0.5, can give a gloomy appearance to daytime outdoor views.

Figure 8-29. Transmittances for of Glass and Plastic Materials

Material	Approximate Transmittance (percent)
Polished Plate/Float Glass	80–90
Sheet Glass	85–91
Heat Absorbing Plate Glass	70–80
Heat Absorbing Sheet Glass	70–85
Tinted Polished Plate	40–50
Figure Glass	70–90
Corrugated Glass	80–85
Glass Block	60–80
Clear Plastic Sheet	80–92
Tinted Plastic Sheet	42–90
Colorless Patterned Plastic	80–90
White Translucent Plastic	10–80
Glass Fiber Reinforced Plastic	5–80
Translucent Sandwich Panels	2–67
Double Glazed-2 Lights Clear Glass	77
Tinted Plus Clear	37–45
Reflective Glass*	5–60

*Includes single glass, double glazed units, and laminated assemblies. Consult manufacturer's material for specific values.

Angular Dependence of Transmittance. The transmittance of glazing materials is a function of the incident angle. Designers can reduce or increase solar gains by orienting the glass of toplighting systems. For instance, glazing tilted at a steep angle to the south admits more direct solar radiation in winter than horizontal glass because of the lower incident angle of sunlight.

Electrically Controlled Glazings. These have transmittance properties that are a function of applied voltage. Currently available products require the application of a low voltage to render them colored. They become clear when the voltage is switched off.⁸⁰ Recent advancements in the development of electrochromic technologies have resulted in glazing assemblies that can switch between 7 and 68% transmittance in two to three minutes.

Translucent Diffusing Materials. The amount of diffusion in materials varies over a wide range, depending on the material and its surface treatment. Generally, transmittance and luminance decrease as diffusion increases. The luminance of highly diffusing materials is nearly constant from all viewing angles (Lambertian). Diffusing materials include translucent and surface-coated or patterned glasses, plastics, translucent sandwich panels,⁸¹ and diffusing glass blocks.

High-Reflectance, Low-Transmittance Materials. Reflective glasses and plastics provide luminance control by having high exterior reflectances. These materials act as one-way mirrors, depending on the ratio of indoor to outdoor illuminance. Their low transmittance often gives outdoor areas an overcast or dark appearance, even on sunny days.²¹ Some selectively admit visible light while reflecting IR wavelengths that would otherwise add to the cooling load.

Directional Transmitting Materials. These include glasses and plastics with prismatic surfaces that are used to obtain directional control of light and luminance. Most of these use the exterior or interior structure of the material to totally internally reflect direct radiation from the sun. In skylights and hollow light pipes, they can reduce throughput in summer and enhance it in winter. In windows under clear sky conditions, they can redirect radiation onto the ceiling and hence deeper into the room while reducing glare close to windows. Recent examples include laser-cut panels and polymer sheets with internal cavities and smooth external surfaces.

Many of these systems interfere with the view through a window and thus are often used above the line of sight. Laser-cut panels used in a flat configuration (e.g., as louver panels) allow preservation of view. Thin films for windows can attenuate direct radiation from high angles while preserving view and admitting most sky radiation from lower angles. These are good for glare control. All of these systems are often referred to as angular-selective, since their effect on radiation strongly depends on the direction of incidence.

Superglazings. High-performance glazings use multiple cavities, often separated by films and usually filled with special gases. They have low-emissivity coatings on one or more glass surfaces to reduce heat transfer.

Specularly Selective Transmitting Materials. These include the various heat-absorbing and reflecting materials that are designed to pass most visible radiation but absorb or reflect a portion of the IR radiation, which would otherwise contribute to cooling loads. Absorbed heat is reradiated indoors and outdoors in approximately equal proportions. Low-emissivity glass comes under this general classification because it selectively admits the visible portion of the spectrum while rejecting the far IR. However, the term "specularly selective glazing" is usually reserved for glass that transmits the visible while rejecting near (and far) IR radiation. The appropriateness of these types of glazing strongly depends on building use and site climate.

Louvers. Louvers may be fixed or adjustable, horizontal or vertical. They are capable of excluding direct sunlight and reducing radiant heat while reflecting sun, sky, and ground light into the interior. In the case of fixed louvers, the spacing and height of the slats should be designed to exclude direct sunlight at common sun angles. Overhangs for sun control are often made with louver elements so that light from the rest of the sky can reach the windows. Louvers are also employed in top-lighting arrangements, sometimes with two sets of slats set at right angles to form an egg crate. Matte textures and high reflectances should be used where possible.

Shade and Draperies. These include opaque and diffusing shades and draperies for excluding or moderating daylight and sunlight, to darken a room, as for projection.

Landscaping. Trees can be effective shading devices for buildings of low elevation if placed in an appropriate position with respect to windows. Deciduous trees provide protection against glare due to direct sun during the warm months but transmit sunlight during the winter. Deciduous vines on louvered overhangs or arbors provide similar seasonal shade.

Exterior Reflecting Elements. Reflective pavements and similar surfaces increase the amount of ground light entering the building. Reflecting materials or finished roofs below windows have the same effect.

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Lighting Calculations

Lighting calculations are performed during the design process to obtain information about lighting system performance. A designer can use the results of calculations to choose between design alternatives or to refine a particular design. Lighting calculations are mathematical models of the complex physical processes that occur within a lighted space. Since these models can never be accurate in every detail, the computations are approximations of real situations.¹

This chapter contains many of the fundamental calculation methods that are used in lighting system analysis, including both simple and complex methods. For methods that apply to specific applications, such as luminaire design, daylighting, floodlighting, roadway lighting, sports lighting, or merchandise lighting, see the special chapters for procedures particular to those areas.

The simplest lighting calculation methods can be performed by hand, whereas the more advanced methods can be performed only by using a computer. More advanced models generally provide more accurate information. Accuracy, for the purpose of this discussion, is defined as the degree to which the calculations agree with reality. In actuality, it is very difficult to achieve perfect agreement, as discussed later in this chapter.

Lighting calculation methods are application driven. The type of information that is desired about a lighting system and the complexity of the lighting condition being analyzed determine which calculation method is best applied to the problem. The aspects that must be evaluated in determining the lighting analysis model to use are the following:

- Information desired
- Equipment choice
- Equipment number and placement
- Space characteristics

It is the responsibility of the designer to determine and use the most appropriate calculation methods for an application. The material presented in this chapter provides the lighting practitioner with information that can be used in making these decisions.

This chapter provides general calculation procedures that are used in the analysis of direct and reflected light. In general, these are fundamental procedures that can be applied to all lighting analysis situations. Also included are specialized calculations commonly used in the evaluation of lighting systems. Finally, a set of example calculations is provided to

illustrate the general algorithm for lighting calculations discussed in this chapter.

BASIC PRINCIPLES

Predicting the radiative transport of luminous flux (or flux transfer) from a source to a receiving surface is fundamental to all lighting calculations. This transport is through air, which is assumed to be nonabsorbing and nonscattering.

Flux transfer is categorized into six types by geometry and emitter type:

1. Point source to a point or differential receiving area
2. Point source to a finite receiving area
3. Diffuse area source to a point or differential receiving area
4. Diffuse area source to a receiving area
5. Nondiffuse area source to a point or differential receiving area
6. Nondiffuse area source to a receiving area

Transfer type 1 is conceptually the simplest and is the easiest to formulate. Transfer types 2, 3, and 4 are obtained from the formulation of type 1 by integrating over the source, the receiving area, or both. Transfer types 5 and 6 are the most complicated, but they are also the most commonly encountered in practice. Light reaching a point or an area is described by *illuminance*, the measure of flux density or the incident flux per unit area.

It is often necessary to know how light reflects from a point or an area. Exitance is the simplest case and is measured as flux density leaving the surface. More complicated is *luminance*, which describes the flux leaving a surface in a particular direction. For exitance and luminance calculations the reflecting properties of the surface must be known. In these cases, methods for predicting illuminance are combined with reflectance information to predict exitances and luminances.

Photometric measurement of a luminaire provides a luminous intensity distribution from which the spatial distribution of flux from the luminaire is obtained. For calculations, the simplest cases are those in which the luminaire is small and can be considered a point. Flux transfer types 1 and 2 can be used. In many cases, the luminaires are large and flux transfer types 3 and 4 are required to provide ade-

quate accuracy. Methods for assessing luminaire size are given below.

Interreflection is the multiple reflection of light among surfaces. It is an important aspect of most interior lighting systems, since it is by interreflection that many interior architectural surfaces acquire a luminance. It is by these luminances that architecture is also revealed and given perceptual form. For some interior lighting systems, interreflection is the only process by which the illuminance on the visual task is produced. Such is the case for indirect electric lighting and many daylighting systems.

Direct Flux Transfer

Flux Transfer Type 1, Point Source to a Point. The illuminance E produced on an area A centered at a point P is related to the luminous intensity of a light source, $I(\theta, \psi)$, as follows. Given the intensity distribution of the light source in spherical coordinates (θ, ψ) , the geometric arrangement is shown in Figure 9-1.

The illuminance E is defined in terms of the flux Φ incident on an area A :

$$E = \frac{\Phi}{A} \quad (9-1)$$

That flux can also be analyzed directionally in terms of the solid angle ω . If the origin of a spherical coordinate system is located at the source, and the area A is small with respect to the distance D , then

$$\omega = \frac{A}{D^2} \cos \xi \quad (9-2)$$

where

D = distance between the source and point P ,

ξ = angle between the normal ($\hat{n}$) to the surface A and direction of the distance D .

The definition of the luminous intensity from the source is used to related Equations 9-2 and 9-1:

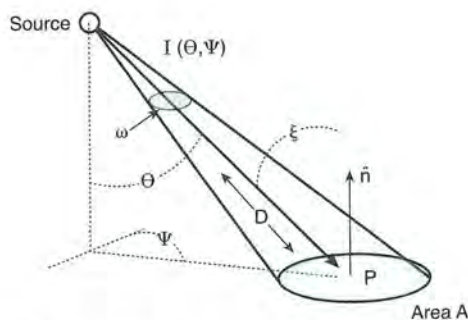


Figure 9-1. Geometric arrangement for the inverse square cosine law.

or

$$I(\theta, \psi) = \frac{\Phi}{\omega}$$

$$\Phi = I(\theta, \psi) \omega \quad (9-3)$$

Substituting this into Equation 9-1 gives

$$E = \frac{I(\theta, \psi) \omega}{A}$$

Substituting Equation 9-2 into this gives

$$E = \frac{I(\theta, \psi) \cos \xi}{D^2} \quad (9-4)$$

Equation 9-4 is the fundamental equation of flux transfer, the so-called inverse square cosine law.² Its validity assumes that of Equation 9-2 and that the luminous intensity is (nearly) constant in the neighborhood of the direction (θ, ψ) .

As the area A (the neighborhood around point P) is made smaller, the solid angle ω becomes smaller and Equation 9-2 becomes more accurate. In the limit of a differential area, dA , the solid angle becomes differential, $d\omega$, and Equation 9-2 is exactly correct. The transfer of flux is conceptually equivalent to an infinitesimally narrow ray of light. The computational consequence of this consideration is that Equation 9-4 describes the illuminance at a differentially small neighborhood around point P or, more briefly, gives the illuminance at P .

Equation 9-2 expresses the solid angle subtended by the area A at a point; the light source is assumed to be coincident with this point. The computational consequence is that Equation 9-4 describes the illuminance from a point source.

The intensity value used in Equation 9-4 is most often obtained by interpolation from values in a table. Intensity distributions are almost always expressed using the two angles of spherical coordinates; thus the required interpolation is over these two angles. Bilinear splines, bicubic splines, and double Fourier series are among the methods used.^{3,4}

Flux Transfer Type 2, Point Source to a Receiving Area.

The flux transferred from a point source to a differential area can be expressed using Equation 9-4. This is integrated over the receiving area to give the flux received by the entire area:

$$d\Phi = E dA$$

$$\Phi = \int E dA$$

$$\Phi = \int \frac{I(\theta, \psi) \cos \xi}{D^2} dA \quad (9-5)$$

The integration is over the receiving area A .

Equation 9-5 can alternatively be solved using Monte Carlo integration.⁵⁻⁷ Conceptually, light rays are traced from the point source P to randomly selected points on the receiving area, A , with Equation 9-4 being evaluated for each ray.

Assuming a random distribution of n points on A , the flux received by A is approximately:

$$\Phi = \sum_{i=1}^n \frac{E_i A}{n}$$

where E_i is the illuminance of A at the receiving point due to ray i . The accuracy of the solution improves with increasing n .

Analytic integration of Equation 9-5 is possible only if the intensity distribution is a simple function and the geometric arrangement is simple.³ Otherwise it is necessary to approximate the area integral of Equation 9-5 with a finite sum. In this case the receiving surface is broken up into small areas, or discretized, and Equation 9-4 is applied to each. The smaller and more numerous the n discrete areas, the more accurate the result:

$$\Phi = \sum_{i=1}^n I(\theta_i, \psi_i) \cos \xi_i \frac{a_i}{D_i^2} \quad (9-6)$$

where

$I(\theta_i, \psi_i)$ = intensity of the point source in the direction of the i th piece of area A ,

ξ_i = incident angle at the i th piece of area A ,

a_i = area of the i th piece of area A ,

D_i = distance between the source and the i th piece of area A .

The average illuminance, $\bar{E}$, can be obtained from either Equation 9-5 or 9-6:

$$\bar{E} = \frac{\Phi}{A}$$

Flux Transfer Type 3, Diffuse Area Source to a Point. In many applications the light source is too large, or the point at which the illuminance is to be calculated is too close, for the conditions of validity for direct use of Equation 9-4 to be met. However, if the source is a diffuse emitter, Equation 9-4 can be used indirectly.

The intensity distribution of a diffuse emitter, in spherical coordinates, is given by

$$I(\theta, \psi) = I_n \cos \theta$$

The distribution is axially symmetric about the direction (0,0), which is also the surface normal (perpendicular). I_n is the luminous intensity in the direction of the surface normal.

Because each differential element dA of the source is a diffuse emitter, the intensity distribution of such an element is

$$dI(\theta, \psi) = \frac{M_{dA} \cos \theta}{\pi} dA$$

where M_{dA} is the exitance of the source at the differential element dA . The illuminance produced at the point P is

$$dE = \frac{M_{dA} \cos \theta \cos \xi}{\pi D^2} dA$$

and the illuminance produced by the entire source is

$$E = \frac{1}{\pi} \int \frac{M_{dA} \cos \theta \cos \xi}{D^2} dA \quad (9-7)$$

If the source exhibits a constant exitance M over its extent, then

$$E = \frac{M}{\pi} \int \frac{\cos \theta \cos \xi}{D^2} dA \quad (9-8)$$

The integration is over the extent of the source.

The quantity that multiplies the exitance M is purely geometric and is called the configuration factor, c .⁸ More simply,

$$E = Mc \quad (9-9)$$

where

$$c = \frac{1}{\pi} \int \frac{\cos \theta \cos \xi}{D^2} dA \quad (9-10)$$

The configuration factor relates the exitance of a diffuse area emitter to the illuminance it produces at a point. It has the limiting values

$$0 \leq c \leq 1$$

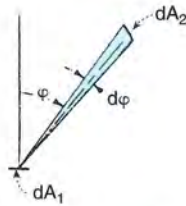
Alternative definitions of the configuration factor are possible. It can be defined as that fraction of the total flux emitted by a differential diffuse emitter that is received directly by an area. The analytic result of this definition is Equation 9-10. This configuration factor has been evaluated for a large number of geometric conditions.⁹ A selection of these equations is given in Figures 9-2 and 9-3.

Equation 9-10 assumes that there are no intervening objects between the diffuse area source A and the point receiver P . If there are, then Equation 9-10 becomes:

$$c = \frac{1}{\pi} \int \frac{V(\theta, \xi) \cos \theta \cos \xi}{D^2} dA$$

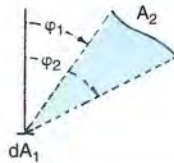
where the visibility term $V(\theta, \xi)$ is 1 if P is visible from dA and 0 if it is hidden by an intervening object. In complex environments such as rooms with partitions and furniture, it is often necessary to solve this equation using numerical integration methods such as the hemicube method⁵⁻⁷ or quasi-Monte Carlo ray casting.⁷ Both approaches are based on Nusselt's analogy (Figure 9-4), where the configuration factor c is equal to the area of the double projection of A onto the base of the hemisphere, divided by the area of the base.

Equation 9-9 can be used to calculate the illuminance at a point produced by any diffuse emitter having a shape for which the configuration factor is known or can be calcu-



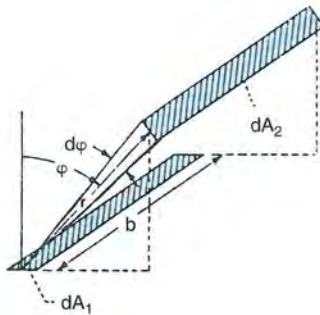
Area dA_1 of differential width and any length, to infinitely long strip dA_2 of differential width and with parallel generating line to dA_1 .

$$C = \frac{\cos \phi}{2} d\phi$$



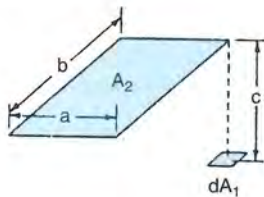
Area dA_1 of differential width and any length to any cylindrical surface A_2 generated by a line of infinite length moving parallel to itself and parallel to the plane of dA_1 .

$$C = \frac{1}{2} (\sin \phi_2 - \sin \phi_1)$$



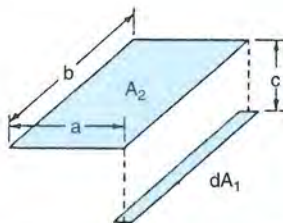
Strip A_1 of length b and differential width, to differential strip dA_2 of same length on parallel generating line.

$$C = \frac{\cos \phi}{\pi} d\phi \arctan \frac{b}{r}$$



Plane element dA_1 to plane parallel rectangle A_2 ; normal to element passes through corner of rectangle. $X = a/c$; $Y = b/c$.

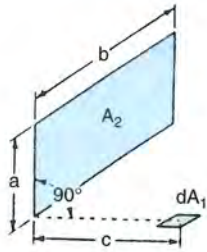
$$C = \frac{1}{2\pi} \left(\frac{X}{\sqrt{1+X^2}} \arctan \frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}} \arctan \frac{X}{\sqrt{1+Y^2}} \right)$$



Strip element dA_1 to rectangle A_2 in plane parallel to strip; strip is opposite one edge of rectangle. $X = a/c$; $Y = b/c$.

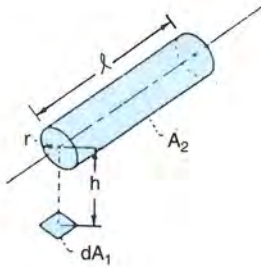
$$C = \frac{1}{\pi Y} \left[\sqrt{1+Y^2} \arctan \frac{X}{\sqrt{1+Y^2}} - \arctan X + \frac{XY}{\sqrt{1+X^2}} \arctan \frac{Y}{\sqrt{1+X^2}} \right]$$

Figure 9-2. Configuration factors (C) for diffuse line and area sources.



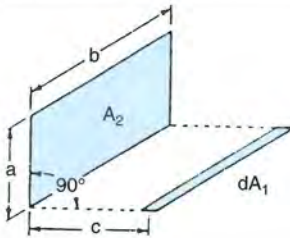
Plane element dA_1 to rectangle A_2 in plane 90° to plane of element. $X = a/b$; $Y = c/b$.

$$C = \frac{1}{2\pi} \left[\arctan \frac{1}{Y} - \frac{Y}{\sqrt{X^2 + Y^2}} \arctan \frac{1}{\sqrt{X^2 + Y^2}} \right]$$



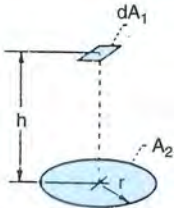
Plane element dA_1 to right circular cylinder A_2 of finite length l and radius r ; normal to element passes through one end of cylinder and is perpendicular to cylinder axis. $L = l/r$; $H = h/r$; $X = (1 + H^2) + L^2$; $Y = (1 - H^2) + L^2$.

$$C = \frac{1}{\pi H} \arctan \frac{L}{\sqrt{H^2 - 1}} + \frac{L}{\pi} \left[\frac{(X - 2H)}{H\sqrt{XY}} \arctan \sqrt{\frac{X(H-1)}{Y(H-1)}} - \frac{1}{H} \arctan \sqrt{\frac{H-1}{H+1}} \right]$$



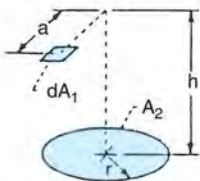
Strip element dA_1 to rectangle A_2 in plane 90° to plane of strip. $X = a/b$; $Y = c/b$.

$$C = \frac{1}{\pi} \left\{ \arctan \frac{1}{Y} + \frac{Y}{2} \ln \left[\frac{Y^2 (X^2 + Y^2 + 1)}{(Y^2 + 1)(X^2 + Y^2)} \right] - \frac{Y}{\sqrt{X^2 + Y^2}} \arctan \frac{1}{\sqrt{X^2 + Y^2}} \right\}$$



Plane element dA_1 to circular disk A_2 in plane parallel to element; normal to element passes through center of disk.

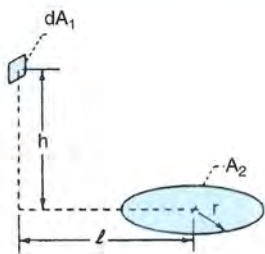
$$C = \frac{r^2}{h^2 + r^2}$$



Plane element dA_1 to circular disk A_2 in plane parallel to element. $H = h/a$; $R = r/a$; $Z = 1 + H^2 + R^2$.

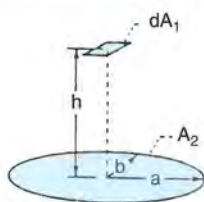
$$C = \frac{1}{2} \left(1 - \frac{1 + H^2 - R^2}{\sqrt{Z^2 - 4R^2}} \right)$$

Figure 9-2. Continued



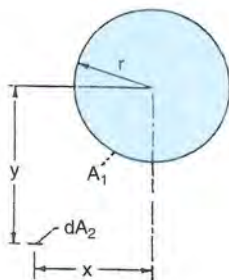
Plane element dA_1 to circular disk A_2 ; planes containing element and disk intersect at 90° . $H = h/l$; $R = r/l$; $Z = 1 + H^2 + R^2$.

$$C = \frac{H}{2} \left(\frac{Z}{\sqrt{Z^2 - 4R^2}} - 1 \right)$$



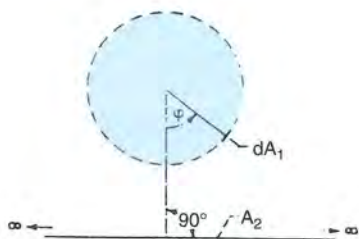
Plane element dA_1 to elliptical plate A_2 in plane parallel to element; normal to element passes through center of plate.

$$C = \frac{ab}{\sqrt{(h^2 + a^2)(h^2 + b^2)}}$$



Strip element dA_2 of any length to infinitely long cylinder A_1 . $X = x/r$; $Y = y/r$.

$$C = \frac{Y}{X^2 + Y^2}$$



Element dA_1 of any length on cylinder to plane A_2 of infinite length and width.

$$C = \frac{1}{2} (1 + \cos \phi)$$

Figure 9-2. Continued

lated. Note that the emitter is assumed to have a uniform diffuse exitance.

Flux Transfer Type 4, Diffuse Area Source to a Receiving Area. If the emitting surface is specified as A_1 and the receiving surface as A_2 , then the flux sent from A_1 to A_2 , or Φ_2 , is

$$\Phi_2 = \int E_{dA_2} dA_2$$

where E_{dA_2} is the illuminance at element dA_2 from all of source A_1 . Substituting for E_{dA_2} using Equation 9-7 gives

$$\Phi_2 = \int \frac{1}{\pi} \int \frac{M_{1dA_1} \cos \theta \cos \xi}{D^2} dA_1 dA_2$$

If the source exhibits a constant exitance M_1 over its extent, then

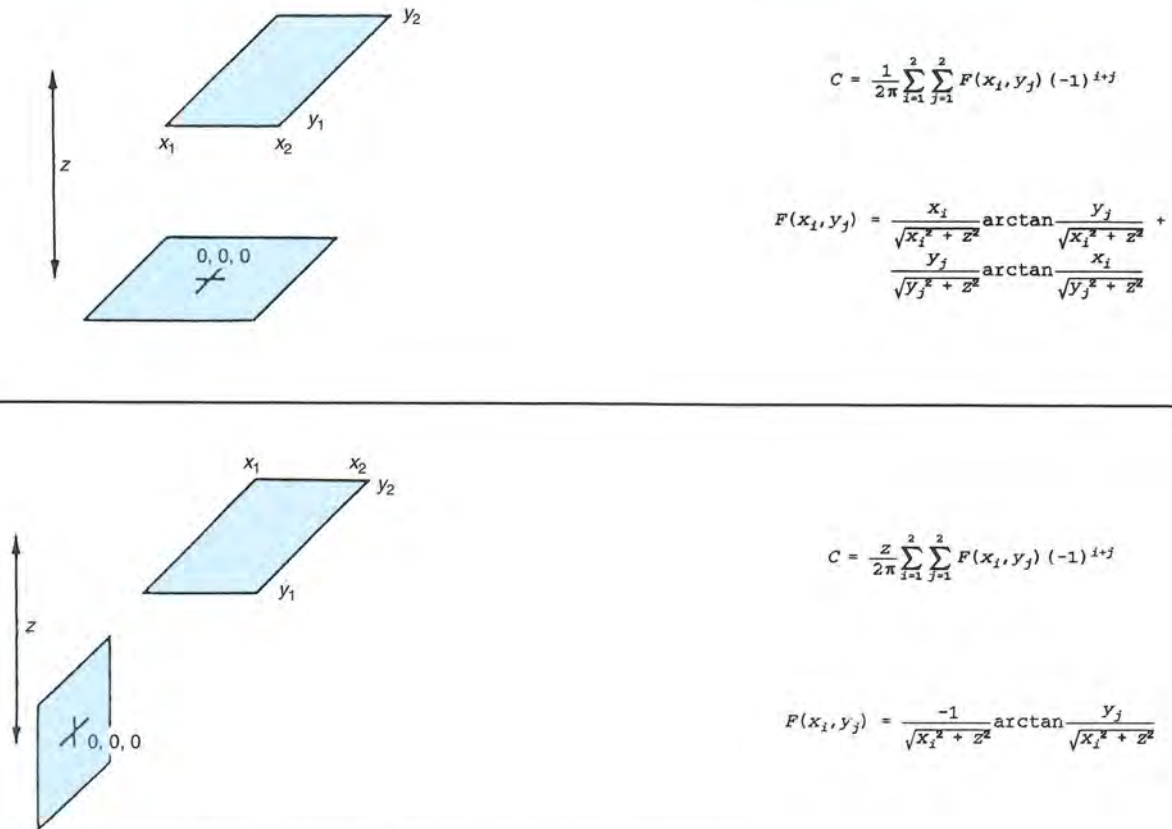


Figure 9-3. General configuration factors (C) for parallel and perpendicular rectangles.

$$\Phi_2 = \frac{M_1}{\pi} \iint \frac{\cos \theta \cos \xi}{D^2} dA_1 dA_2 \quad (9-11)$$

The integration is over the extent of the source and the extent of the illuminated area. The quantity that multiplies the exitance M_1 is purely geometric. It is customary to divide it by the area A_1 so that it is the fraction of flux leaving surface A_1 that reaches A_2 . This is called the form factor $f_{1 \rightarrow 2}$.⁸ Subscripts for form factors are necessary to indicate the direction in which flux is transferred. We have

$$f_{1 \rightarrow 2} = \frac{1}{\pi A_1} \iint \frac{\cos \theta \cos \xi}{D^2} dA_1 dA_2 \quad (9-12)$$

With this definition, Equation 9-11 becomes

$$\Phi_2 = M_1 A_1 f_{1 \rightarrow 2}$$

The average illuminance, $\bar{E}_2$, produced on surface A_2 is then

$$\bar{E}_2 = \frac{\text{flux emitted by } A_1 \text{ reaching } A_2}{A_2}$$

$$\bar{E}_2 = \frac{M_1 A_1 f_{1 \rightarrow 2}}{A_2}$$

Form factors and areas relate the exitance of a diffuse area emitter to the average illuminance produced on a receiving surface. The form factors have the limiting values

$$0 \leq f \leq 1$$

and exhibit reciprocity:

$$A_1 f_{1 \rightarrow 2} = A_2 f_{2 \rightarrow 1}$$

Application of reciprocity gives

$$\bar{E}_2 = M_1 f_{2 \rightarrow 1} \quad (9-13)$$

The equation for the form factor has been evaluated for a large number of geometric conditions. A selection of these equations is given in Figures 9-5 and 9-6.

Equations 9-9 and 9-13 have wide application for the calculation of illuminance and average illuminance produced by any form of diffuse emitter. Most large architectural surfaces exhibit a diffuse reflectance and therefore are diffuse

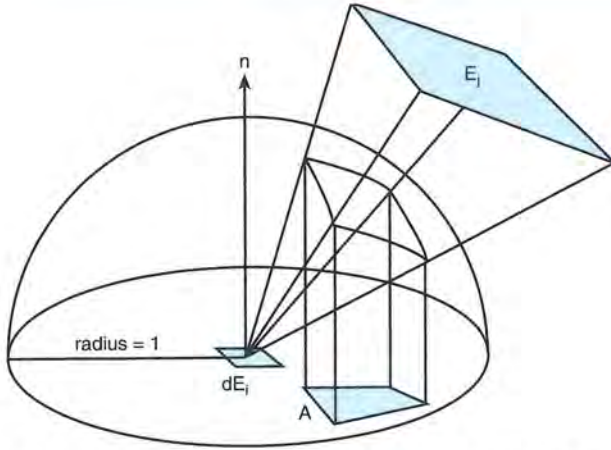


Figure 9-4. Construction of Nusselt's analogy for diffuse radiative transfer from a point to an area.

emitters by reflection. The illuminance produced by such surfaces can be calculated using Equations 9-9 and 9-13. This includes surfaces made luminous by interreflection of light and indirectly lighted surfaces.

It is difficult to analytically evaluate the form factor between two areas with arbitrary geometry, and even more difficult in the presence of occluding objects.^{10,11} Approximate evaluations can be obtained using Monte Carlo ray casting.^{6,7}

Skylights and windows are commonly approximated as diffuse emitters by reason of the type of transmittance they exhibit. Equations 9-9 and 9-13 can be used in these cases also.

If an area diffuse emitter does not have a uniform exitance, it can be discretized into smaller elements, each of which has a nearly uniform exitance. The illuminance produced by each element is then calculated by repeated application of Equation 9-9 or 9-13. The total effect is obtained by adding the individual illuminances.

Flux Transfer Type 5, Nondiffuse Area Source to a Point. Nondiffuse area emitters are significantly more difficult to treat than diffuse emitters. If a far-field intensity distribution is available for the luminaire, Equation 9-4 can be used in certain cases. If the distance from the luminaire to the calculation point is greater than five times the largest dimension of the luminaire, then treating the luminaire as a point source using Equation 9-4 gives a computational accuracy of approximately 5% or better.

For points closer to the luminaire, an assumption can be made about homogeneity (surface uniformity) that permits a useful approximation to be made.³ Under this assumption, the intensity distribution of any differential element of the emitter, $dI(\theta, \psi)$, is proportional to the intensity distribution, $I(\theta, \psi)$, of the entire luminaire. The constant of proportionality is the ratio of the area dA of the differential element to the area A of the entire luminaire. That is,

$$dI(\theta, \psi) = I(\theta, \psi) \frac{dA}{A}$$

The differential element is then treated as a point source, and Equation 9-4 is used to express the differential illuminance it produces:

$$dE = \frac{dI(\theta, \psi) \cos \xi}{D^2} = \frac{1}{A} \frac{I(\theta, \psi) \cos \xi}{D^2} dA$$

Integration over the surface of the luminaire gives

$$E = \frac{1}{A} \int \frac{I(\theta, \psi) \cos \xi}{D^2} dA \quad (9-14)$$

Analytic integration of Equation 9-14 is possible only if the intensity distribution is a simple function and the geometric arrangement is simple. Otherwise it is necessary to approximate the area integral of Equation 9-14 with a finite sum. In this case, the luminaire is discretized into small areas. The smaller and more numerous the discrete areas, the more accurate the result:

$$E = \frac{1}{A} \sum_i I(\theta_i, \psi_i) \cos \xi_i \frac{a_i}{D_i^2} \quad (9-15)$$

where the summation is over all the discrete pieces of the luminaire, and

$I(\theta_i, \psi_i)$ = intensity of the i th piece of the luminaire surface to point P ,

ξ_i = incident angle for flux from the i th piece of the luminaire surface,

a_i = area of the i th piece of the luminaire surface,

D_i = distance between the i th piece of the luminaire surface and point P ,

A = area of the luminaire surface.

Equation 9-15 has wide application for the calculation of illuminance produced by luminaires with nondiffuse distributions.

Flux Transfer Type 6, Nondiffuse Area Source to a Receiving Area. If the nondiffuse emitting surface is specified as A_1 and the receiving surface as A_2 , then the flux Φ_2 sent from A_1 to A_2 is

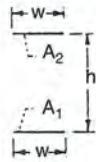
$$\Phi_2 = \int E_{dA_2} dA_2$$

where E_{dA_2} is the illuminance at element dA_2 from all of source A_1 .

Under the same assumption of luminaire homogeneity described above, Equation 9-14 can be used to express E_2 :

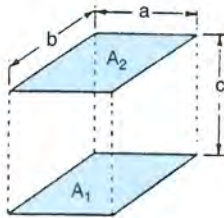
$$E_2 = \int \frac{1}{A_2} \int \frac{I(\theta, \psi) \cos \xi}{D^2} dA_1 dA_2 \quad (9-16)$$

The double area integrals usually cannot be evaluated analytically, and a double area summation is used as an approx-



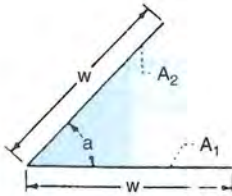
Two infinitely long, directly opposed plates A_1 and A_2 of the same finite width. $H = h/w$.

$$F_{1-2} = F_{2-1} = \sqrt{1 + H^2} - H$$



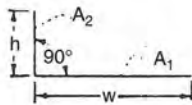
Identical, parallel, directly opposed rectangles A_1 and A_2 .
 $X = a/c$; $Y = b/c$.

$$F_{1-2} = \frac{2}{\pi XY} \left[\ln \left(\frac{(1 + X^2)(1 + Y^2)}{1 + X^2 + Y^2} \right)^{1/2} + X\sqrt{1 + Y^2} \arctan \frac{X}{\sqrt{1 + Y^2}} + \right. \\ \left. Y\sqrt{1 + X^2} \arctan \frac{Y}{\sqrt{1 + X^2}} - X \arctan X - Y \arctan Y \right]$$



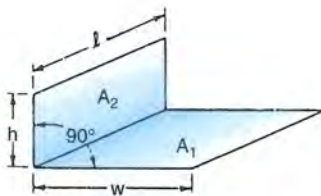
Two infinitely long plates A_1 and A_2 of equal finite width w , having one common edge, and at an included angle α to each other.

$$F_{1-2} = F_{2-1} = 1 - \sin \frac{\alpha}{2}$$



Two infinitely long plates A_1 and A_2 of unequal widths h and w , having one common edge, and at an angle of 90° to each other. $H = h/w$.

$$F_{1-2} = \frac{1}{2} [1 + H - \sqrt{1 + H^2}]$$



Two finite rectangles A_1 and A_2 of same length, having one common edge, and at an angle of 90° to each other.
 $H = h/l$; $W = w/l$.

$$F_{1-2} = \frac{1}{\pi HW} \left(W \arctan \frac{1}{W} + H \arctan \frac{1}{H} - \sqrt{H^2 + W^2} \arctan \frac{1}{\sqrt{H^2 + W^2}} + \right. \\ \left. \frac{1}{4} \ln \left[\frac{(1 + H^2)(1 + W^2)}{(1 + H^2 + W^2)} \right] \frac{H^2(1 + H^2 + W^2)}{(1 + H^2)(W^2 + H^2)} \right)^{1/2} \left[\frac{H^2(1 + H^2 + W^2)}{(1 + H^2)(H^2 + W^2)} \right]^{1/2} \right)$$

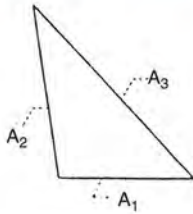
Figure 9-5. Radiative transfer theory form factors (F) for diffuse area sources.

imation. In this case the luminaire and the receiving surface are discretized into small areas. The smaller and more numerous the discrete areas, the more accurate the result:

$$E_2 = \frac{1}{A_2} \sum_i \sum_j I(\theta_{ij}, \psi_{ij}) \cos \xi_{ij} \frac{a_{1i} a_{2j}}{D_{ij}^2} \quad (9-17)$$

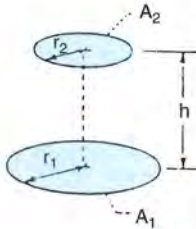
where the summation is over all the discrete pieces of luminaire and the discrete pieces of the receiving surface, and

$I(\theta_{ij}, \psi_{ij})$ = intensity of the i th piece of the luminaire in the direction of the j th piece of the receiving surface,



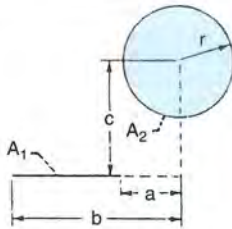
Infinitely long enclosure formed by three plane areas A_1 , A_2 and A_3 .

$$F_{1-2} = \frac{A_1 + A_2 - A_3}{2A_1}$$



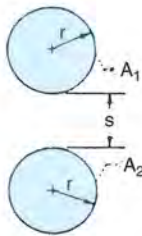
Parallel circular disks A_1 and A_2 with centers along the same normal. $R_1 = r_1/h$; $R_2 = r_2/h$; $X = 1 + (1 + R_2^2)/R_1^2$.

$$F_{1-2} = \frac{1}{2} \left[X - \sqrt{X^2 - 4 \left(\frac{R_2}{R_1} \right)^2} \right]$$



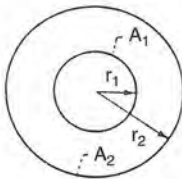
Infinitely long plane A_1 of finite width to parallel infinitely long cylinder A_2 .

$$F_{1-2} = \frac{r}{b-a} \left[\arctan \frac{b}{c} - \arctan \frac{a}{c} \right]$$



Infinitely long parallel cylinders A_1 and A_2 of the same diameter. $X = 1 + s/2r$.

$$F_{1-2} = F_{2-1} = \frac{1}{\pi} \left[\sqrt{X^2 - 1} + \arcsin \left(\frac{1}{X} \right) - X \right]$$



Concentric cylinders A_1 and A_2 of infinite length.

$$\begin{aligned} F_{1-2} &= 1 \\ F_{2-1} &= \frac{r_1}{r_2} \\ F_{2-2} &= 1 - \frac{r_1}{r_2} \end{aligned}$$

Figure 9-5. Continued

ξ_{ij} = incident angle of flux from the i th piece of the luminaire,

a_{1i} = area of the i th piece of luminaire,

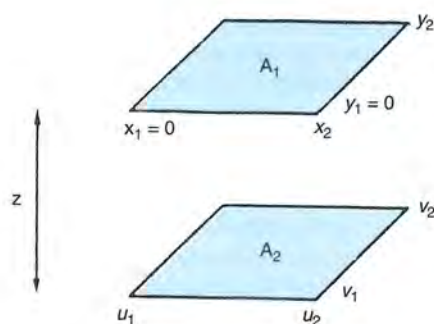
a_{2j} = area of the j th piece of the receiving surface,

D_{ij} = distance between the i th piece of the luminaire and the j th piece of the receiving surface,

A_1 = area of the luminaire surface,

A_2 = area of the receiving surface.

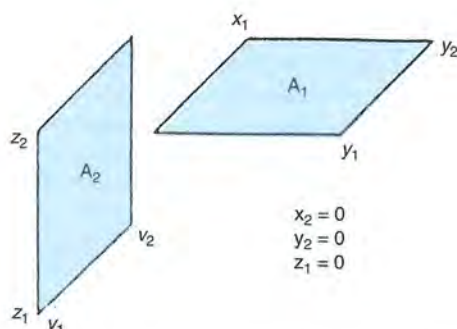
Equation 9-16 can alternatively be evaluated using quasi-Monte Carlo ray casting,⁵⁻⁷ where the distribution of points that rays are sent from the emitting surface A_1 to the receiv-

Parallel rectangles A_1 and A_2 .

$$F_{1-2} = \frac{z^2}{\pi A_1} \sum_{i=1}^2 \sum_{j=1}^2 \sum_{k=1}^2 \sum_{m=1}^2 H(u_i, v_j, x_k, y_m) (-1)^{i+j+k+m}$$

$$H(u_i, v_j, x_k, y_m) = b\sqrt{1+a^2} \arctan \frac{b}{\sqrt{1+a^2}} + \frac{a\sqrt{1+b^2} \arctan \frac{a}{\sqrt{1+b^2}}}{\frac{1}{2} \ln(1+a^2+b^2)}$$

$$a = (x_k - u_i)/z \quad b = (y_m - v_j)/z$$

Perpendicular rectangles A_1 and A_2 .

$$F_{1-2} = \frac{1}{2\pi A_1} \sum_{i=1}^2 \sum_{j=1}^2 \sum_{k=1}^2 \sum_{m=1}^2 G(v_i, z_j, x_k, y_m) (-1)^{i+j+k+m}$$

$$G(v_i, z_j, x_k, y_m) = a\sqrt{c^2 + b^2} \arctan \frac{a}{\sqrt{c^2 + b^2}} + \frac{1}{4} (a^2 - b^2 - c^2) \ln(a^2 + b^2 + c^2)$$

$$\begin{aligned} a &= y_m - v_i & b &= \bar{z} - z_j & c &= x_k - \bar{x} \\ \bar{z} &= z\text{-coordinate of surface } A_1 \\ \bar{x} &= x\text{-coordinate of surface } A_2 \end{aligned}$$

Figure 9-6. General expressions for form factors (F) between parallel and perpendicular rectangles.

ing surface A_2 is weighted according to the photometric distribution of the nondiffuse emitting surface.

All of the previous types of analyses are summarized in Figure 9-7. The equation to be used for illuminance calculations is determined by the size of the source, the size of the receiving element, and the nature of the intensity distribution of the source. If the distance between the source and the analysis point is less than five times the largest dimension of the source, the source is considered an area source for the purposes of calculation. This five times rule is discussed in the next section.

Photometry as the Basis for Calculations

Intensity distributions are used to specify the spatial distribution characteristics of a light source. This description treats the source as a point and gives the luminous intensity. The set is sufficiently large to provide a complete description of the spatial distribution of flux.

The luminous intensity of a light source or luminaire is calculated from measurements of illuminance. Illuminances are obtained at a convenient measurement distance that defines an imaginary sphere with a radius equal to the measurement dis-

tance. The sphere center coincides with a fiducial point inside the luminaire. This so-called photometric center is often the origin of the coordinate system used for calculations.¹²

If the source is assumed to be a point, then the intensity and the illuminance are related by Equation 9-4. If the illuminance measurements are made with the surface normal of the illuminance probe oriented to the photometric center, then the cosine of the viewing angle equals 1 and Equation 9-4 becomes

Figure 9-7. Flux Transfer Equations

Size of Source	Size of Receiving Element	Distribution	Appropriate Equation
Point	Point	Diffuse	(9-4)
	Point	Nondiffuse	(9-4)
	Area	Diffuse	(9-9)*
Area	Point	Diffuse	(9-9)*
	Point	Nondiffuse	(9-15)
	Area	Diffuse	(9-13)*
	Area	Nondiffuse	(9-17)

An asterisk (*) signifies that these equations are available for specific geometries (see Figures 9-2, 9-3, 9-5, and 9-6).

$$E_t = \frac{I}{D_t^2}$$

or

$$I = E_t D_t^2 \quad (9-18)$$

where

I = luminous intensity,
 E_t = illuminance measurement,
 D_t = measurement (test) distance.

The luminous intensity is distance invariant, since the product $E_t D_t^2$ is distance invariant. Thus, the illuminance at any distance is given by Equation 9-4.

In the photometry of luminaires, Equation 9-18 is generally applied to obtain a relative value of the luminaire's intensity in a particular direction. The magnitude is then determined through photometry of the bare lamps in a procedure known as relative photometry.

Far-Field Photometry

Assuming the luminaire to be a point source permits the illuminance produced under any geometric circumstance to be calculated. The computational value of intensity distributions rests on the assumption that illuminance varies proportionally to the reciprocal of the distance squared and to the cosine of the incident angle.

Only a point light source produces illuminances that always vary as the inverse squared distance. However, regardless of the luminaire size, it is always possible to choose a distance, D_r , sufficiently large so that illuminances produced

at distances greater than D_r do vary (nearly) as the inverse squared distance. Yamauti¹³ and Fock¹⁴ first showed this for diffuse emitters. For these emitters D_r is five times the maximum dimension of the emitter. This five times rule permits a computational accuracy of at worst 2% for diffuse emitters. In far-field photometry, a distance of at least D_r is used to make the illuminance measurements from which the luminous intensities are calculated. These intensities can then be used to calculate illuminances at distances greater than D_r , treating the luminaire as a point source. Most commercial photometry uses far-field photometry.

Illuminance calculations that assume the luminaire to be a point source at distances less than D_r are likely to be inaccurate. As a guide to the inaccuracies that can be expected, Figure 9-8 shows an illuminance error curve for a square diffuse emitter. The error, in percent of the correct value, is given as a function of the ratio of the calculation distance D to the luminaire dimension. The five times rule requires this ratio to be 5 or larger. Comparison between measurements and predictions using real luminaires gives similar results.¹⁵

It should be noted that intensity distributions other than that of a diffuse emitter have different values of D_r .¹⁶ However, it is customary to apply the five times rule to most indoor luminaire photometry.

Near-Field Photometry

Near-field photometry describes the spatial flux distribution of a luminaire in a manner permitting accurate illuminance calculations at distances less than D_r . Near-field photometry is particularly important for analyzing indirect lighting systems. Two types of near-field photometry have been developed expressly for improving computational accuracy.

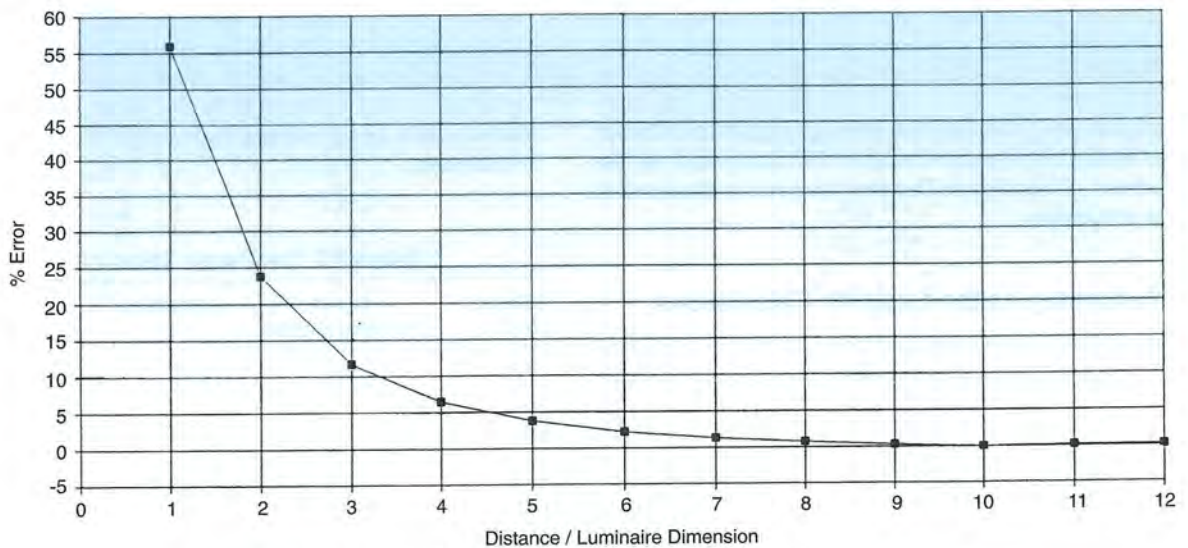


Figure 9-8. Demonstration of the five-times rule for photometric measurements.

Application-distance photometry uses test distances that are equal to the distances at which illuminance calculations are made.¹⁷⁻¹⁹ No assumptions about distance invariance are made. In this case the luminaire must be treated as a point source for calculations. Since illuminance calculations are likely to be made at many distances, application-distance photometry provides intensity distributions for several test distances.

Luminance-field photometry^{16,20,21} measures and reports the luminance distribution of the luminaire as viewed from a set of points completely surrounding the luminaire. All points are the same distance from the luminaire photometric center. Precisely stated, the data describe a four-dimensional scalar field of luminance. From these luminance data, illuminance can be calculated at any distance and orientation from the luminaire. Luminance-field photometric measurements can be made using a CCD video camera;²² however, the quantity of data can be difficult to manage.²³

Reflection Properties of Surfaces

Useful special cases of reflectance are perfectly diffuse and perfectly specular reflectances. These cases of the spatial distribution permit great simplification of calculations involving the reflection of light from surfaces.

Perfectly diffuse reflection is that for which the luminous intensity in a given direction is proportional to the cosine of the declination angle from the perpendicular to the surface. The flux reflected from a diffuse surface is not a function of the incident direction or the azimuthal angle. Thus, the reflecting surface exhibits a luminance independent of viewing angle.

Perfectly specular reflection is that in which flux is reflected at the mirror angle to the incident direction. That is, the angle of the reflected flux is equal to that of the incident direction with respect to the direction perpendicular to the surface, and the azimuthal separation of the exitant and incident flux is exactly 180°.

Many surfaces and finishes used in architecture exhibit a reflectance that is sufficiently diffuse to be considered perfectly diffuse. This is important for computational purposes, since they can be considered diffuse emitters regardless of the incident direction of the light.

In some cases, assumptions about diffuseness lead to very inaccurate results. An example of this is the calculation of the luminance of visual tasks, such as pencil marks on paper, etched marks on a rule, and roadway surfaces. The bidirectional reflectance distribution function (BRDF) of a surface must be used in these cases.²⁴

In addition to simplifying the spatial distribution characteristics of reflectance, it is often permissible (and necessary) to simplify its spectral characteristics. All surfaces exhibit a reflectance that varies with the wavelength of the incident light. The reflectance reported for a particular surface is usually obtained by integrating the proportion of light reflected from the surface at all visible wavelengths. Although the reflectance so defined changes if the spectrum of

the illuminant changes, it is a useful approximation to assume that the reflectance is spectrally flat. The surface is assigned a "gray reflectance" equal to the integrated value. Thus, it is assumed that the surface exhibits the same reflectance regardless of the spectral power distribution of incident light used in calculations. This is referred to as the "gray assumption."

Although this simplifies calculations and usually introduces only small errors, difficulties can arise. The reflectance of a surface with a deeply saturated color usually has a significant spectral reflectance only in a narrow band of wavelengths. Use of a light source spectrally different from that used in making a reflectance standard can then lead to large errors.

Interreflection of Light

Some of the light incident on an architectural surface is absorbed, and some is reflected. The reflected portion radiates to other surfaces, where it is absorbed and reflected again. This can be thought of as happening an infinite number of times. The phenomena of repeated exchange of light by multiple reflection is called interreflection.²⁵⁻²⁸ Architectural surfaces are made luminous by interreflection, as well as by light that reaches them directly from sources such as luminaires and windows. The exitances that these surfaces exhibit under these circumstances are said to be those at luminous equilibrium. That is, they are the exitances present when the rate at which light is being provided by luminaires and daylighting is balanced by the rate at which it is being absorbed by surfaces. These exitances are called final exitances, in contrast with initial exitances, which are those produced directly by light from luminaires or daylighting, before the process of interreflection.

Surfaces made luminous by interreflections become additional sources of light that should be considered when determining illuminance. The illuminance produced by reflected light is termed the interreflected component. In most architectural settings it is usually assumed that the surfaces involved exhibit a diffuse reflectance and therefore are diffuse emitters. They can then be treated as diffuse area sources, and the illuminance is calculated using the equations for a diffuse area source, involving configuration factors and surface exitance. The total interreflected component at an analysis point is

$$E_{\text{inter}} = \sum_{i=1}^n c_{i \rightarrow p} M_i \quad (9-19)$$

where

$$c_{i \rightarrow p} = \text{configuration factor from surface } i \text{ to point } p,$$

$$M_i = \text{diffuse exitance of surface } i.$$

Thus, calculating the interreflected component of illuminance requires the determination of the final exitance of surfaces that are luminous by interreflection.

The most useful calculation procedure for determining the final exitances is the finite-element method.²⁹⁻³¹ The surfaces in the space are discretized, and each element is assumed to have a different but uniform exitance. In most cases it also can be assumed that the reflectances are perfectly diffuse. The accuracy of the calculated luminance pattern depends on the size of the zones and on the degree to which the reflectances are diffuse.

Modeling room surfaces as discrete elements not only allows an approximation to the actual exitance pattern in the room, but such modeling can also represent the effect of doors, windows, bulletin boards, and chalkboards.²⁹ Since these surfaces generally differ from the walls in reflectance, their exitance is also different, as is their effect on the illuminance within the space.

The degree to which the pattern of exitance in the enclosure is represented by the assemblage of discrete zone exitances depends on the zone size. A highly variable directional component, such as one that can be produced by an indirect lighting or wall-washing system, may require a small discretization of surfaces. This permits an accurate model of the large luminance gradient.

In advanced models, interior obstructions such as partitions, shelves, and furniture can also be considered.^{32,33} Other methods have been developed to reduce the amount of work required to solve such systems,³⁴⁻³⁶ and approximations for calculations in spaces with interior obstructions have also been developed.³⁷

Numerous techniques based on radiative flux transfer theory^{5,6} (also known as radiosity methods) and ray tracing³⁸ have been developed by the computer graphics community. While these techniques have been developed primarily for architectural rendering, they are based on physical principles^{5,23} and so can be applied to illumination engineering problems as well.

Radiosity methods model perfectly diffuse reflections, whereas ray tracing techniques are best suited to modeling specular reflections. However, hybrid techniques have been developed to accurately model both diffuse and specular reflections.^{23,39,40}

The Radiative Transfer Equation^{5-7,10,11,22,23,38-43}

To obtain the equations for calculating interreflection, a flux balance equation is written for each element. It equates the total flux leaving an element to the total incident flux multiplied by the element's reflectance. The total incident flux has both a direct component due to electric and daylight sources and an interreflected component due to the flux from all the other elements. The equality expressing the flux balance exists when all interreflections are taken into account. For the i th element of a radiative transfer system, the equation is

$$M_i = M_{0i} + \rho_i(f_{i \rightarrow 1}M_1 + f_{i \rightarrow 2}M_2 + \dots + f_{i \rightarrow m-1}M_{m-1} + f_{i \rightarrow m}M_m) \quad (9-20)$$

This can be written for each surface element in the system, and a set of linear, independent, simultaneous equations results. Expressed in matrix form, this gives

$$\begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_m \end{bmatrix} = \begin{bmatrix} M_{01} \\ M_{02} \\ \vdots \\ M_{0m} \end{bmatrix} + \begin{bmatrix} \rho_1 f_{1 \rightarrow 1} & \rho_1 f_{1 \rightarrow 2} & \dots & \rho_1 f_{1 \rightarrow m-1} & \rho_1 f_{1 \rightarrow m} \\ \rho_2 f_{2 \rightarrow 1} & \rho_2 f_{2 \rightarrow 2} & \dots & \rho_2 f_{2 \rightarrow m-1} & \rho_2 f_{2 \rightarrow m} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \rho_m f_{m \rightarrow 1} & \rho_m f_{m \rightarrow 2} & \dots & \rho_m f_{m \rightarrow m-1} & \rho_m f_{m \rightarrow m} \end{bmatrix} \times \begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_m \end{bmatrix} \quad (9-21)$$

where

- m = number of zones in the system,
- M_i = exitance of the i th zone, due to direct and interreflected flux (the equation is solved for these values),
- ρ_i = diffuse reflectance of the i th zone,
- M_{0i} = exitance due to the direct component on the i th zone (due to luminaires and daylight sources),
- $f_{i \rightarrow j}$ = form factor from zone i to zone j (note that for planar zones, $f_{i \rightarrow i} = 0$).

For simple geometries, the form factors can be computed using the equations found for parallel and orthogonal rectangles in Figures 9-5 and 9-6. For complex geometries, and especially for environments with occluding objects, it is necessary to use numerical integration methods such as hemicubes and Monte Carlo ray casting.

The above matrix equation can be rewritten in terms of the illuminance on each surface. This form is particularly valuable when one or more of the reflectances is assigned a value of zero, since then the illuminance striking each element is independent of the element's reflectance:

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} = \begin{bmatrix} E_{01} \\ E_{02} \\ \vdots \\ E_{0m} \end{bmatrix} + \begin{bmatrix} \rho_1 f_{1 \rightarrow 1} & \rho_1 f_{1 \rightarrow 2} & \dots & \rho_1 f_{1 \rightarrow m-1} & \rho_1 f_{1 \rightarrow m} \\ \rho_2 f_{2 \rightarrow 1} & \rho_2 f_{2 \rightarrow 2} & \dots & \rho_2 f_{2 \rightarrow m-1} & \rho_2 f_{2 \rightarrow m} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \rho_m f_{m \rightarrow 1} & \rho_m f_{m \rightarrow 2} & \dots & \rho_m f_{m \rightarrow m-1} & \rho_m f_{m \rightarrow m} \end{bmatrix} \times \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} \quad (9-22)$$

The simplest way to solve these large matrix finite-element systems is to use the method of iteration.^{5,40} The iteration begins by setting the vector M equal to the exitance vector M_0 in Equation 9-21, using this as an initial estimate of the system. This initial estimate is then used on the right-hand side of the equation to generate another estimate of the solution vector on the left.

Various iteration methods may be employed. Jacobi iteration exactly simulates physical reflections and absorption of light within an environment.²³ Faster convergence is usually obtained with Gauss-Seidel iteration,⁴³ typically within five to ten iterations for simple environments with relatively few elements.

Gauss-Seidel iteration has the disadvantage that the entire form factor matrix is required for each iteration. This limits the number of elements that can be modeled using computer simulations. A variation of Southwell iteration called progressive refinement⁶ is preferred in that only one column of the form factor matrix is required for each iteration. This permits the modeling of complex environments with hundreds of thousands of elements, with convergence attained in a few minutes using desktop computers.⁴⁰

It should be noted that maintained values of the exitance might differ from initial values. Should computation of maintained values be required, the surface reflectances used in the computation of the reflected component should be the reflectances expected under maintained conditions in the environment. Additionally, a light loss factor should be used in the calculation of the initial exitances.

Implementation of the Flux Balance Model

The simplest example of a radiative transfer problem solved by this method is a system with two surfaces. In this case, two equations in two unknowns result. The solution is

$$M_1 = \frac{M_{01} + M_{02} \rho_1 f_{1 \rightarrow 2}}{1 - \rho_1 \rho_2 f_{1 \rightarrow 2} f_{2 \rightarrow 1}} \quad (9-23a)$$

$$M_2 = \frac{M_{02} + M_{01} \rho_2 f_{2 \rightarrow 1}}{1 - \rho_1 \rho_2 f_{1 \rightarrow 2} f_{2 \rightarrow 1}} \quad (9-23b)$$

where

M_1 = final exitance of surface 1, taking account of interreflection,

M_2 = final exitance of surface 2, taking account of interreflection,

M_{01} = initial exitance of surface 1,

M_{02} = initial exitance of surface 2,

ρ_1 = diffuse reflectance of surface 1,

ρ_2 = diffuse reflectance of surface 2,

$f_{2 \rightarrow 1}$ = form factor from surface 2 to surface 1,

$f_{1 \rightarrow 2}$ = form factor from surface 1 to surface 2.

These equations provide a way to estimate the effects of interreflection in situations involving only two surfaces, or

where only two elements of a large system participate in interreflection.

Another example of how a simple flux balance model can be applied to the analysis of a lighting system is the three-surface model used in the lumen method (Figure 9-9).⁴⁴⁻⁴⁶ The geometric arrangement is an empty rectangular room with recessed lighting equipment. The lighting system provides a general uniform illuminance on the workplane. Perfectly diffuse reflectances on all surfaces are assumed, and the same reflectance is assumed for the four wall surfaces. This allows the four walls to be treated as one surface. The average illuminance on the floor is to be calculated.

For the purposes of the finite-element procedure, then, there are three elements or zones in this room: ceiling, walls, and floor. The surfaces have initial exitances M_{0c} , M_{0w} , and M_{0f} respectively. These initial exitances are due to the flux falling on the surfaces from the luminaires within the room.

Since there are interreflections, the final exitances M_c , M_w , and M_f can be expressed as follows:

$$M_c = M_{0c} + \rho_c (M_w f_{c \rightarrow w} + M_f f_{c \rightarrow f}) \quad (9-24)$$

$$M_w = M_{0w} + \rho_w (M_c f_{w \rightarrow c} + M_w f_{w \rightarrow w} + M_f f_{w \rightarrow f}) \quad (9-25)$$

$$M_f = M_{0f} + \rho_f (M_c f_{f \rightarrow c} + M_w f_{f \rightarrow w}) \quad (9-26)$$

where

M_c = final ceiling exitance,

M_w = final wall exitance,

M_f = final floor exitance,

M_{0c} = initial ceiling exitance,

M_{0w} = initial wall exitance,

M_{0f} = initial floor exitance,

ρ_f = floor reflectance,

ρ_w = wall reflectance,

ρ_c = ceiling reflectance,

$f_{f \rightarrow c}$ = form factor from floor to ceiling,

$f_{f \rightarrow w}$ = form factor from floor to walls,

$f_{w \rightarrow c}$ = form factor from walls to ceiling,

$f_{w \rightarrow w}$ = form factor from walls to walls,

$f_{w \rightarrow f}$ = form factor from walls to floor,

$f_{c \rightarrow w}$ = form factor from ceiling to walls,

$f_{c \rightarrow f}$ = form factor from ceiling to floor.

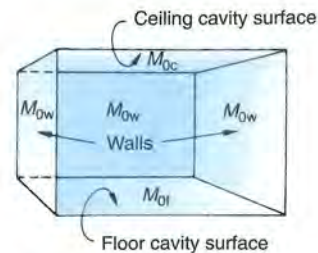


Figure 9-9. Radiative transfer theory diagram.

With these three equations and the form factors, any interior illuminance or exitance can be determined. The above set of simultaneous equations is the basis for generating the tables of the coefficients of utilization, the wall exitance coefficients, and the ceiling cavity exitance coefficients.

This simple geometry permits the remaining six form factors to be determined from the form factor, $f_{c \rightarrow f}$, between floor and ceiling, using reciprocity and the flux balance requirement (the sum of all form factors leaving a single surface must sum to 1.0 for a closed system).

$$f_{f \rightarrow c} = f_{c \rightarrow f} \quad (9-27)$$

$$f_{c \rightarrow w} = f_{f \rightarrow w} = 1 - f_{c \rightarrow f} \quad (9-28)$$

$$f_{w \rightarrow c} = f_{w \rightarrow f} = \frac{A_c}{A_w} (1 - f_{c \rightarrow f}) \quad (9-29)$$

$$f_{w \rightarrow w} = 1 - 2f_{w \rightarrow c} \quad (9-30)$$

In these equations, A_c and A_w are the surface areas of the ceiling and walls, respectively. This three-surface model is the simplest of all flux transfer models for interior lighting calculations. It assumes that flux strikes each surface in a uniform manner and does not include variations in illuminance across any surface. In accordance with the Commission Internationale de l'Éclairage (CIE) practice and for the lumen method described below, the standard lighting coefficient tables are based upon a length-to-width ratio of 1.6 and given as a function of the room cavity ratio (RCR) only. Figure 9-10 gives numerical values for the various form factors.

The lumen method extends the utility of this three-surface model by letting the ceiling and floor surfaces be virtual surfaces that are actually openings into rectangular cavities. These virtual surfaces are assigned effective reflectances. The top virtual surface is a plane containing the

luminaires, and the cavity that this virtual surface represents extends from the luminaires up to the ceiling. The bottom virtual surface is the workplane, and the cavity that this virtual surface represents extends from the workplane down to the floor. Note that the average illuminance onto the workplane is its final exitance divided by its effective reflectance.

Although more complicated, exactly the same procedure can be used for models of radiative transfer in a room that uses more than three surfaces (the finite-element method). Complex models can have thousands of discrete elements as each surface in the room is divided into a collection of smaller zones.³⁴⁻³⁶ The result is a more detailed knowledge of the room surface exitance distributions.

Monte Carlo Ray Tracing⁷

One disadvantage of the simple flux balance models is that they can model reflections only from perfectly diffuse surfaces. Although this is adequate for most lighting calculations and architectural renderings, it does not provide sufficient information for estimating veiling reflections from specular surfaces and glare calculations.

Ray tracing techniques provide a more realistic model for the behavior of light, including reflection from specular surfaces and refraction by transparent objects. Reflections from diffuse surfaces can be approximated by reflecting hundreds of rays in random directions from each incident ray.⁶ By providing appropriate weights to different directions of ray incidence and reflection, arbitrary bidirectional reflectance distribution functions can also be modeled.

Ray tracing is mathematically equivalent to radiative flux transfer between point emitters and receivers. Whereas evaluation of Equation 9-22 provides estimates for the illuminance of each surface element, Monte Carlo ray tracing provides similar estimates for random points on each surface. Illuminances for surface elements can then be obtained through Monte Carlo integration.

Rays can be traced either from the light sources into the environment (photosimulation)^{6,39} or from the observer into the environment (path tracing).^{23,38,39} Photosimulation methods are useful in that they provide accurate exitances for all surface elements in the environment. Path tracing methods are useful in that they provide accurate luminances for all surfaces within the observer's field of view, including veiling and specular reflections.

The disadvantage of ray tracing techniques is that millions to hundreds of millions of rays must be evaluated in order to reduce the variance of the solutions to acceptable levels. While various statistical techniques can be used to ensure that randomly chosen ray directions transport on average the maximum amount of flux between surfaces,⁶ convergence of the radiative transfer equation using ray tracing techniques is typically slow in comparison to finite element methods.

Figure 9-10. Form Factors for a Zonal-Cavity System

RCR	$F_{w \rightarrow w}$	$F_{w \rightarrow c}$ $F_{w \rightarrow f}$	$F_{c \rightarrow w}$ $F_{f \rightarrow w}$	$F_{c \rightarrow f}$ $F_{f \rightarrow c}$
0	0.000	0.500	0.000	1.000
1	.133	.434	.173	.827
2	.224	.388	.311	.689
3	.298	.351	.421	.579
4	.361	.320	.511	.489
5	.415	.292	.585	.415
6	.463	.269	.645	.355
7	.504	.248	.694	.306
8	.540	.230	.735	.265
9	.573	.214	.769	.231
10	.601	.199	.798	.202

The length:width ratio is 1.6:1.

Lighting Simulation Programs

The radiative transfer equation can be solved using finite element (radiosity) methods, ray tracing techniques, and hybrid approaches. These approaches are collectively referred to as global illumination algorithms by the computer graphics community.²³ Unlike simpler computer graphics techniques, global illumination algorithms are based on physical principles. Because they model the physical behavior of light, they can be used in lighting simulation software programs to create photorealistic architectural renderings and perform sophisticated illumination engineering calculations.

APPLICATION ISSUES

Characterizing Light for Calculation Purposes

Lighting calculations are generally divided into two components for the purpose of determining the amount of light reaching a point in space. The direct component comprises light reaching the point directly from the luminaires or windows. The interreflected component is comprised of light reaching the same point from surfaces due to interreflections.

Direct Component. The direct component must be determined for points of interest on the workplane and for any reflecting surfaces considered in the analysis. The contribution to the reflecting surfaces is used to provide the starting condition for interreflections. On the workplane, the direct component may have special importance because it is the principal component responsible for veiling reflections. Under a typical direct lighting system, the direct component provides the majority of the total illuminance on the workplane. In outdoor lighting situations, the direct component may be the only light that a point receives. The direct component can be determined using the inverse square law or one of the area source methods if the luminaires are large compared to the distances involved. Methods have been developed that take advantage of either special geometries or intensity distributions.⁴⁷⁻⁵¹

Interreflected Component. In most lighting calculations, the interreflected component requires the most time-consuming calculation. The amount of work involved in solving the large matrix problem is proportional to the square of the number of elements involved. To determine the interreflected component, the initial illuminance or direct component must first be determined at each of the discrete elements. In most cases, the value at the center of each element is used as an approximation of the average illuminance across an element. If the elements are sufficiently small, the error involved in this assumption is minimal. Large elements require more careful determinations of the average initial

exitance, such as integration methods or calculation of several points to get an average.

Determination of the interreflected component is critical in situations where it is likely to be large relative to the direct component. Situations where this may be true include coves, valences, and indirect lighting applications. It is important that the discretization scheme and calculation model being used for the direct component be capable of providing a light distribution that accurately models that provided by the lighting system.^{3,32} Near-field photometry may be required for such calculations.^{22,42}

In some cases, a much less rigorous interreflection model may be applied. If the direct component is certain to dominate at the analysis points of interest, it may be possible to use a rather simple interreflected component calculation method involving larger and fewer room surface elements. When using large elements, it is important to remember that the value at the center of a large surface does not necessarily approximate the average across it. The total luminous flux striking the surface should be determined and then divided by the area to determine the average illuminance on the surface.

In the simplest approximation, the room is approximated with three surfaces, as used in the lumen method described below, and the interreflected component is calculated using the three surface exitances that result from the lumen method approximation.

Light Loss Factors⁵²⁻⁵⁵

Light loss factors adjust lighting calculations from a controlled laboratory environment to actual field conditions. They represent differences in lamp lumen output, luminaire output, and surface reflectances between the two sets of conditions. Calculations based on laboratory data alone are likely to provide unrealistically high values if not modified by light loss factors.

Light loss factors are divided into two groups: recoverable and nonrecoverable (Figure 9-11). Recoverable factors are those that can be changed by regular maintenance, such as cleaning and relamping luminaires and cleaning or painting room surfaces. Nonrecoverable factors are those attributed to equipment and site conditions and cannot be changed with normal maintenance.

Light loss factors are assumed to represent independent effects and are therefore multiplicative. The total light loss factor (LLF) is the product of all the applicable factors listed in Figure 9-11. No factor should be ignored (set equal to 1) until investigations justify doing so. Lighting calculations should not be attempted until all light loss factors are considered.

Nonrecoverable Factors. The nonrecoverable factors usually are not controlled by lighting maintenance procedures. Some exist initially and continue through the life of the in-

Figure 9-11. Light Loss Factors

Nonrecoverable	
Luminaire ambient temperature factor	
Heat extraction thermal factor	
Voltage-to-luminaire factor	
Ballast factor	
Ballast-lamp photometric factor	
Equipment operating factor	
Lamp position (tilt) factor	
Luminaire surface depreciation factor	
Recoverable	
Lamp lumen depreciation factor	
Luminaire dirt depreciation factor	
Room surface dirt depreciation factor	
Lamp burnout factor	

stallation, either being of such little effect as to make correction needless, or being too costly to correct. However, all should be studied because they can diminish the planned luminous output of the lighting system.

Luminaire Ambient Temperature Factor. The effect of ambient temperature on the output of some fluorescent lamp luminaires is considerable. Variations in temperature, within the range of those normally encountered in interiors, have little effect on the light output of incandescent and high-intensity discharge lamp luminaires but appreciably affect the light output of fluorescent luminaires. The luminaire ambient temperature factor is the fractional lumen loss of a fluorescent luminaire due to internal luminaire temperatures differing from the temperatures at which photometry was performed. This factor should take into consideration any variation in the temperature around the luminaire, the means and conditions of mounting the luminaire, and the use of any insulation in conjunction with the application of the luminaire.

Generally, firm data on this factor are not available but can be estimated on the following basis. Luminaire photometry is performed in 25° C (77° F) ambient still air. For each degree of rise in ambient temperature above this value, the cold-spot temperature on a fluorescent lamp rises by about 0.6° C (1° F). The effect of lamp temperature rise can be estimated from the manufacturer's literature, recognizing that lamps in luminaires generally operate at temperatures greater than the optimum. Judgment must be applied to factors such as the effect of open versus enclosed luminaires, possible air movement, and the fact that the plenum temperature has a greater effect than the room temperature on recessed luminaires.

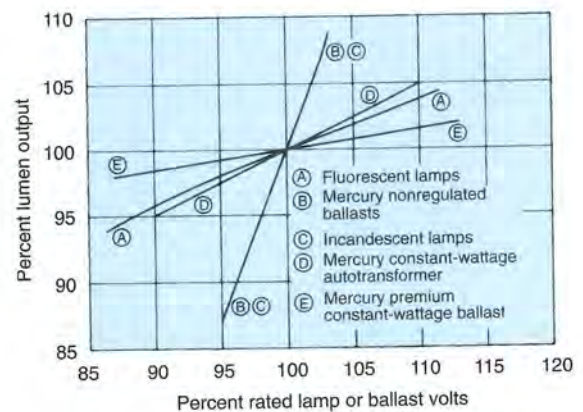
Heat Extraction Thermal Factor. Air-handling fluorescent luminaires are integrated with the HVAC system as a means of introducing or removing air. This has an effect on lamp temperature and consequently on lamp lumens. The heat extraction thermal factor is the fractional lumen loss or gain due to the air flow. Generally, manufacturers provide specific luminaire test data for this factor at various air flows. Typically, the factor approaches a constant value for

air flows in excess of 10 to 20 ft³/min through the lamp compartment of a luminaire.

Voltage-To-Luminaire Factor. In-service voltage is difficult to predict, but high or low voltage at the luminaire affects the luminous output of most luminaires. For incandescent units, a 1% voltage deviation causes approximately a 3% change in lumen output. For mercury lamp luminaires with high-reactance ballasts there is a change in lumen output of approximately 3% for each 1% change in primary voltage deviation from rated ballast voltage. When regulated-output ballasts are used, the lamp lumen output is relatively independent of primary voltage within the design range. The luminous output of fluorescent luminaires using conventional magnetic ballasts changes approximately 1% for each 2.5% change in primary voltage. Figure 9-12 shows these variations in graphic form. Different characteristics apply to electronic or energy-saving magnetic ballasts and depend on specific design parameters (see Chapter 6, Light Sources).

Ballast Factor. The lumen output of fluorescent lamps depends on the ballast used to drive the lamps. The lumen output from lamps on commercial ballasts generally differs from that of lamps on the standard reference ballast used for determining rated lumens. For this reason, a multiplicative ballast factor is required to correct nominal rated lamp lumens to actual luminaire performance. The ballast factor is the fractional flux of a fluorescent lamp or lamps operated on the actual ballast divided by the flux when operated on the standard (reference) ballast specified for rating lamp lumens. Ballast factors are determined in accordance with the American National Standard Methods of Measurement of Fluorescent Lamp Ballasts.³⁶ Manufacturers should be consulted for necessary factors. Data on ballast factors for electronic ballasts are available.³⁷ Some representative values are shown in Chapter 6, Light Sources. Note that when uncertified ballasts are used, there may be no reliable data available.

The ballast factor depends on the lamp as well as on the

**Figure 9-12. Light output change due to voltage change.**

ballast, so that a ballast factor developed for a standard lamp does not apply when, for example, an energy-conserving lamp is used, even though the ballast is the same. Magnetic ballasts bearing the label of Certified Ballast Manufacturers (CBM) have a ballast factor that is not less than 0.925 for standard 30- and 40-W rapid start lamps; the ballast factor for such ballasts is frequently estimated at between 0.94 and 0.95. The ballast factor for highly loaded rapid start lamps is 0.95, and for various low-wattage lamps is 0.90.

However, the American National Standards Institute (ANSI)⁵⁶ test method for the ballast factor specifies that the test be performed on a cold ballast (for convenience in testing). Significant temperature rise occurs for operating ballasts in luminaires. This causes additional lumen loss, usually on the order of 1.5%, but values as high as 2.5 to 3.5% have been reported. Consequently, a conservative estimate of the operational ballast for a CBM certified ballast would be 0.93.

Ballast-Lamp Photometric Factor. Fluorescent lamp luminaire photometry is performed at a standard ambient temperature of 25° C (77° F). The lamp temperature differs from this value when rated lamp lumens are determined. The consequent lamp lumen change from rated lumens is incorporated into the photometric data. The lamp temperature within the luminaire depends on the particular combination of ballast (standard magnetic, energy-efficient magnetic, or electronic) and lamps (standard loading, reduced-power, and energy-efficient). For this reason the photometric data apply only to the specific lamp and ballast types used in the tests. This also applies to the derived data such as coefficients of utilization and exitance coefficients.

Lamp lumen variations cause a change in the magnitude but not in the spatial distribution of fluorescent luminaire intensity. Consequently, all photometric data can be corrected by a multiplicative factor for ballast and lamp types that differ from those used in the photometric tests. This factor is the ballast-lamp photometric factor, and it is measured for a specific ballast-lamp combination in relation to those used in the luminaire photometry. Values for it are available as part of the luminaire photometric report or from the manufacturer. Note that this factor includes adjustment for lamp and ballast changes at the photometric test temperature of 25° C (77° F). The luminaire ambient temperature factor is a separate correction for differences between the laboratory and the expected luminaire installation temperature.

Equipment Operating Factor. The lumen output of high-intensity discharge (HID) lamps depends on the ballast, the lamp operating position, and the effect of power reflected from the luminaire back onto the lamp. These effects are collectively incorporated in the equipment operating factor (EOF), which is defined as the ratio of the flux of an HID lamp-ballast-luminaire combination, in a given operating position, to the flux of the lamp-luminaire combination operating in the position for rating the lamp lumens and using the standard (reference) ballasting specified for rating lamp

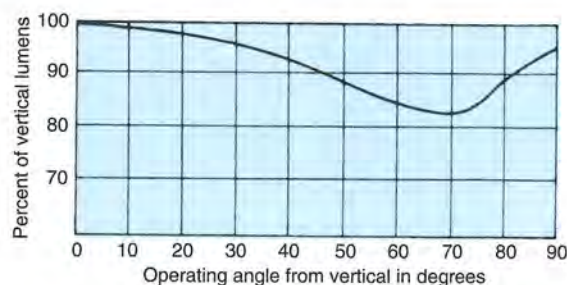


Figure 9-13. Lumen output for HID lamps as a function of operating position.

lumens. Equipment operating factors are determined in accordance with the IES Approved Method for Determining Luminaire-Lamp-Ballast Combination Operating Factors for High-Intensity Discharge Luminaires.⁵⁸

Lamp Position or Tilt Factor (Part of EOF). For HID lamps, the lamp position factor (sometimes known as the tilt factor) is the ratio of the flux of a HID lamp in a given operating position to the flux when the lamp is operated in the position at which the lamp lumens are rated. This factor is determined at constant lamp wattage and constitutes part of the equipment-operating factor. The lamp position factor is reasonably consistent for mercury lamp types. However, for metal halide lamps it is variable from lamp to lamp and depends on the operating history; thus, it is not actually a constant even for a given lamp.^{59,60} Figure 9-13 presents typical average data for the lamp position factor; manufacturers should be consulted regarding specific lamp types.

Luminaire Surface Depreciation Factor. Luminaire surface depreciation results from adverse changes in metal, paint, and plastic components that result in reduced light output. Surfaces of glass, porcelain, or processed aluminum have negligible depreciation and can be restored to original reflectance. Baked enamel and other painted surfaces have a permanent depreciation because all paints are porous to some degree. Among plastics, acrylic is least susceptible to change, but its transmittance may be reduced by use over a period of 15 to 20 years in certain atmospheres. For the same usage, polystyrene has lower transmittance than acrylic and depreciates faster.

Because of the complex relationship between the light-controlling elements of luminaires using more than one type of material (such as a lensed troffer), it is difficult to predict losses due to deterioration of materials. Also, for luminaires with one type of surface, the type of atmosphere in the installation affects the losses. No factors for this effect are available at present.

Recoverable Factors. Recoverable factors always need to be considered in determining the total light loss factor. The magnitude of each depends on the maintenance procedures to be used in addition to the physical environment and the lamps and luminaires to be installed.

Lamp Lumen Depreciation Factor. The lumen outputs of lamps change gradually and continuously over their operating lives, even with constant operating conditions. In almost all cases, the lumens decrease. The lamp lumen depreciation (LLD) factor is the fraction of the initial lumens produced at a specific time during the life of the lamp. Information about LLD as a function of the hours of lamp operation is available from manufacturers' tables and graphs for lumen depreciation and mortality of the chosen lamp. The rated average life should be determined for the expected number of hours per start; it should be known when burnouts begin in the lamp life cycle. From these facts, a practical group relamping cycle can be established, and then, based on the hours elapsed to lamp removal, the LLD factor can be determined. Consult Chapter 6, Light Sources, or manufacturers' data for LLD factors. 70% of average rated life is the recommended criterion for lamp replacement for both group and spot relamping programs. It should be noted that some electronic ballasting systems compensate to varying degrees for change in lamp lumen output through life, either by an average correction or by feedback control.

Luminaire Dirt Depreciation Factor. The accumulation of dirt on luminaires results in a loss in light output, and therefore a loss on the workplane. This loss is known as the luminaire dirt depreciation (LDD) factor and is determined as follows:

1. The luminaire maintenance category is selected from manufacturers' data or by using Figure 9-14.
2. The atmosphere (one of five degrees of dirt conditions) in which the luminaire operates is found as follows. Dirt in the atmosphere comes from two sources: that passed from adjacent air, and that generated by work done in the vicinity. Dirt may be classified as adhesive, attracted, or inert, and it may come from intermittent or constant sources. Adhesive dirt clings to luminaire surfaces by its stickiness, whereas attracted dirt is held by electrostatic force. Inert dirt varies in accumulation, from practically nothing on vertical surfaces to as much as a horizontal surface holds before the dirt is dislodged by gravity or air circulation. Examples of adhesive dirt are grease from cooking, particles from machine operation borne by oil vapor, particles borne by water vapor as in a laundry, and fumes from metal-pouring operations or plating tanks. Examples of attracted dirt are hair, lint, fibers, and dry particles that are electrostatically charged from machine operations. Examples of inert dirt are non-sticky, uncharged particles such as dry flour, sawdust, and fine cinders. Figures 9-15 and 9-16 may be useful for evaluating the atmosphere. Figure 9-16 is intended to evaluate the atmosphere-dirt category. Factors 1 to 5 should be assessed and inserted into the spaces in the table, since they are required

Figure 9-14. Procedure for Determining Luminaire Maintenance Categories

Maintenance Category	Top Enclosure	Bottom Enclosure
I	1. None	1. None
II	1. None 2. Transparent with 15 percent or more uplight through apertures 3. Translucent with 15 percent or more uplight through apertures 4. Opaque with 15 percent or more uplight through apertures	1. None 2. Louvers or baffles
III	1. Transparent with less than 15 percent upward light through apertures 2. Translucent with less than 15 percent upward light through apertures 3. Opaque with less than 15 percent uplight through apertures	1. None 2. Louvers or baffles
IV	1. Transparent unapertured 2. Translucent unapertured 3. Opaque unapertured	1. None 2. Louvers
V	1. Transparent unapertured 2. Translucent unapertured 3. Opaque unapertured	1. Transparent unapertured 2. Translucent unapertured
VI	1. None 2. Transparent unapertured 3. Translucent unapertured 4. Opaque unapertured	1. Transparent unapertured 2. Translucent unapertured 3. Opaque unapertured

To assist in determining Luminaire Dirt Depreciation (LDD) factors, luminaires are separated into six categories (I through VI). To arrive at categories, luminaires are arbitrarily divided into sections, a Top Enclosure and a Bottom Enclosure, by drawing a horizontal line through the light center of the lamp or lamps. The characteristics listed for the enclosures are then selected as best describing the luminaire. Only one characteristic for the top enclosure and one for the bottom enclosure should be used in determining the category of a luminaire. Percentage of uplight is based on 100% for the luminaire. The maintenance category is determined when there are characteristics in both enclosure columns. If a luminaire falls into more than one category, the lower numbered category is used.

to describe the conditions of the space. The "Area Adjacent to Task Area" column represents the area separated from but adjacent to the area in which the luminaire operates (which is the "Area Surrounding Task"). The "Filter Factor" column contains the

Figure 9-15. Evaluation of Operating Atmosphere

Type of Dirt*	Area Adjacent to Task Area			Filter Factor (percent of dirt passed)	Area Surrounding Task			Sub Total
	Intermittent Dirt	Constant Dirt	Total		From Adjacent	Intermittent Dirt	Constant Dirt	
Adhesive Dirt	+	=	×	=	+	+	=	
Attracted Dirt	+	=	×	=	+	+	=	
Inert Dirt	+	=	×	=	+	+	=	
Total of Dirt Factors:								
0-12 = Very Clean		13-24 = Clean		25-36 = Medium		37-49 = Dirty		49-60 = Very Dirty

*See step 2 under Luminaire Dirt Depreciation.

Factors for use in the table are 1: Cleanest conditions imaginable; 2: Clean, but not the cleanest; 3: Average; 4: Dirty, but not the dirtiest; 5: Dirtiest conditions imaginable.

percentages of dirt allowed to pass from the adjacent atmosphere to the surrounding atmosphere. The "From Adjacent" column indicates the net amount of such dirt that can pass through. This category might include, for example, an open window with a filter factor of 1.0 (no filtering at all), or an air-conditioning system with a filter factor of 0.1 (90% of dirt is filtered out). The total of all the numbers in the "Subtotal" column is a number up to 60 and can be translated into the applicable atmosphere-dirt category listed at the bottom of the table.

- From the appropriate luminaire maintenance category curve of Figure 9-17, the applicable dirt condition curve and the proper elapsed time in months of the planned cleaning cycle, the LDD factor is found. For example, if the category is I, the atmos-

phere is dirty, and cleaning occurs every 20 months, the LDD is approximately 0.80. An alternative procedure to Figure 9-17 is to use the fitted equation

$$LDD = e^{-At^B} \quad (9-31)$$

where the constants A and B are found from Figure 9-18, based on the luminaire maintenance category and the atmosphere condition involved, and t is time in decimal years (e.g., 1 yr 6 mo is entered as 1.5 yr).

Room Surface Dirt Depreciation Factor. The accumulation of dirt on room surfaces reduces the amount of luminous flux reflected and interreflected to the workplane. To take this into account, Figure 9-19 has been developed to provide room surface dirt depreciation (RSDD) factors for use in calculating maintained average illuminance levels. These factors are determined as follows:

Figure 9-16. Five Degrees of Dirt Conditions

	Very Clean	Clean	Medium	Dirty	Very Dirty
Generated Dirt	None	Very little	Noticeable but not heavy	Accumulates rapidly	Constant accumulation
Ambient Dirt	None (or none enters area)	Some (almost none enters)	Some enters area	Large amount enters area	Almost none excluded
Removal or Filtration	Excellent	Better than average	Poorer than average	Only fans or blowers if any	None
Adhesion	None	Slight	Enough to be visible after some months	High—probably due to oil, humidity, or static	High
Examples	High grade offices, not near production; laboratories; clean rooms	Offices in older buildings or near production; light assembly; inspection	Mill offices; paper processing; light machining	Heat treating; high-speed printing; rubber processing	Similar to dirty but luminaires within immediate area of contamination

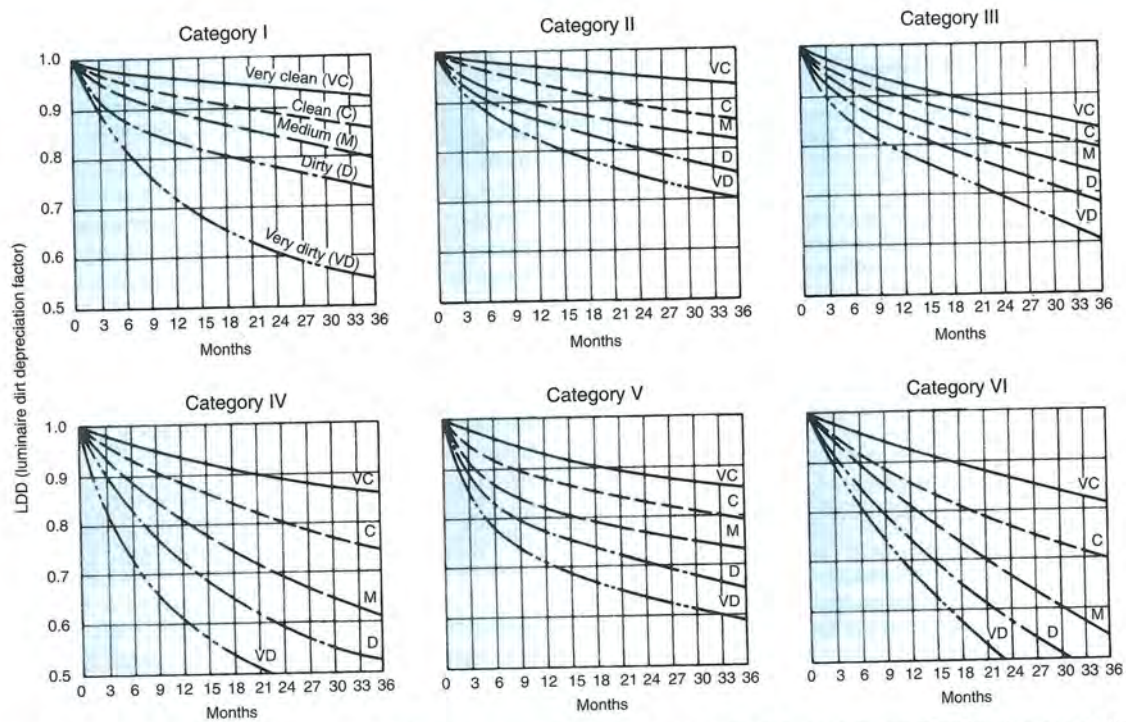


Figure 9-17. Luminaire Dirt Depreciation (LDD) factors for six luminaire categories (I through VI) and for five degrees of dirtiness as determined from Figures 9-14 or 9-15.

1. From one of the five curves in Figure 9-19, find the expected dirt depreciation using Figure 9-15 or 9-16 as a guide to atmospheric dirt conditions, together with an estimate of the time between cleanings. For example, if the atmosphere is dirty and room surfaces are cleaned every 24 months, the expected dirt depreciation is approximately 30%.

2. Knowing the expected dirt depreciation (step 1), the type of luminaire distribution (see Chapter 7, Luminaires) and the room cavity ratio, determine the RSDD factor from Figure 9-19. For example, for a dirt depreciation of 30%, a direct luminaire, and a room cavity ratio (RCR) of 4, the RSDD would be 0.92.

Figure 9-18. Luminaire Dirt Depreciation Constants Used for Calculating the LDD for Six Luminaire Categories and Five Degrees of Dirtiness

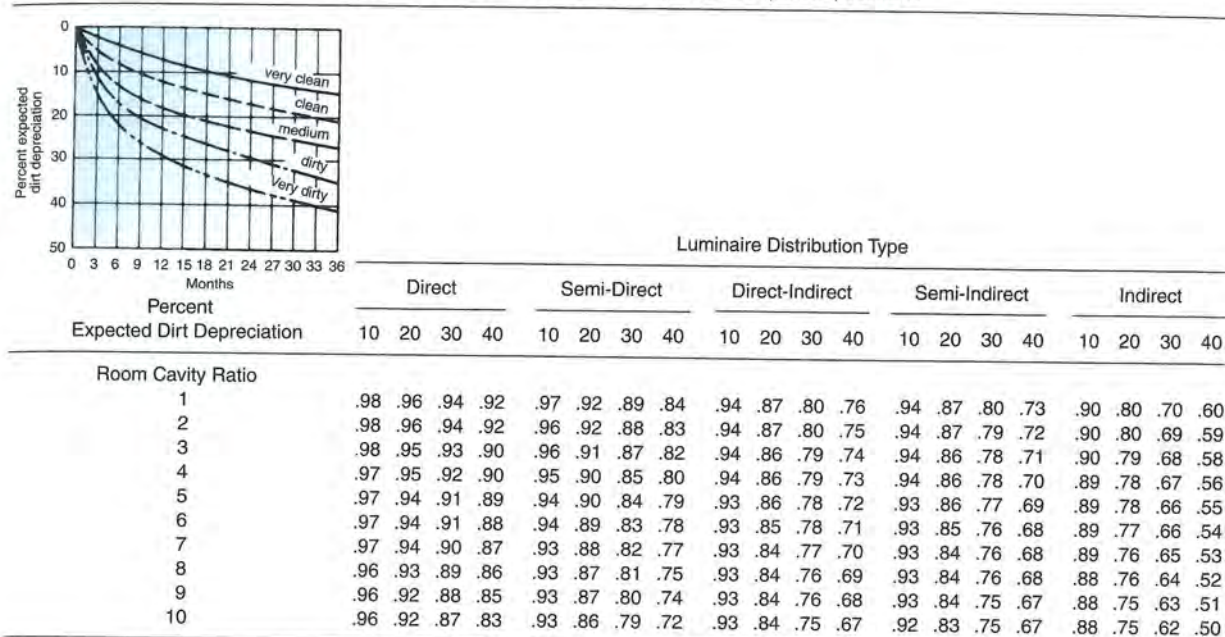
Luminaire Maintenance Category	B	A				
		Very Clean	Clean	Medium	Dirty	Very Dirty
I	.69	.038	.071	.111	.162	.301
II	.62	.033	.068	.102	.147	.188
III	.70	.079	.106	.143	.184	.236
IV	.72	.070	.131	.216	.314	.452
V	.53	.078	.128	.190	.249	.321
VI	.88	.076	.145	.218	.284	.396

Lamp Burnout Factor. Lamp burnouts contribute to light loss. If lamps are not replaced promptly after burnout, the average illuminance is decreased proportionally. In some instances, more than just the faulty lamp may be lost. For example, when series sequence fluorescent ballasts are used and one lamp fails, both lamps go out. The lamp burnout (LBO) factor is the ratio of the number of lamps remaining lighted to the total, for the maximum number of burnouts permitted.

Manufacturers' mortality statistics should be consulted for the performance of each lamp type to determine the number expected to burn out before the time of planned replacement is reached. In practice, the number of lamp burnouts is a reflection of the quality of the lighting services program.

Total Light Loss Factor. The total light loss factor (LLF) is simply the product of all the contributing factors described above. Where factors are not known, or not applicable, they are assumed to be unity. If the total LLF is excessive, it may be desirable to reselect the luminaire.

Figure 9-19. Room Surface Dirt Depreciation (RSDD) Factors



STATISTICAL QUANTITIES

When lighting calculations and system modeling are required, it is important that an appropriate method be applied to predict system performance. If an inappropriate model is used, the results can be inaccurate. A designer should therefore have knowledge of the capabilities and limitations of the different modeling options and their applications.

Averages

An average value is the simplest way of specifying the performance of a lighting system. "Average" usually refers to the mean of several calculated or measured values. The greater the number of values, the more accurate the mean. Grids of calculation or measurement points are usually used, often formed by a rectangular array of rows and columns. Point spacing is determined by the accuracy requirements for the average. The accuracy of an average obtained from a calculation or measurement grid can be estimated by doubling the number of points in the grid and determining the size of the change in the average. A large change may indicate the need for more points. This process can be repeated until the change in the average is small enough to indicate that sufficient accuracy has been attained.

An average can be accurate but not indicative of variation in values. For this reason, the average illuminance (or an average of any other quantity) should be used only when the distribution is expected to be relatively uniform across an area. When a localized lighting system is desired, such as for

a reception desk in a lobby, bimodal, or multimodal distributions result, and an average-illuminance calculation method should not be used. An average value can be used to design the system for the general circulation space, but for the task area, individual point source calculations should be used to characterize the task lighting.

In general, an average value alone is not sufficient to fully describe or evaluate lighting system performance. Information on the uniformity of the lighting is also important. The following two subsections consider methods for describing the uniformity of lighting across an area.

Minima and Maxima

If a large number of analysis points are used for calculation, then the variability of the lighting can be evaluated and the minimum and maximum values can be determined and located. The minima and maxima can be important indicators of the quality of the design, particularly if they deviate significantly from the desired average. In some design situations, maximum and minimum design values may be specified. In evaluating whether or not a particular design is acceptable, it is important to focus on the critical task areas within a space. Minima often occur around the perimeter of a room or lighted area, where tasks may not be located. Levels below the target level may be acceptable if they are not at actual task locations. In other design situations, the maximum value may be critical. For example, it may not be desirable to have room surface luminances that exceed a particular value. This is the case in the lighting

recommendations for spaces with visual display terminals (VDTs).

Uniformity is often expressed in terms of a ratio of two quantities. Examples are maximum to minimum, maximum to average, and average to minimum. Different design situations warrant different uses of these measures.

Criterion Ratings

The maximum and minimum values provide little information about the overall distribution of a particular photometric or derived quantity across a space. The criterion rating is a convenient way to obtain greater detail regarding the distribution of a quantity across a space. The criterion rating is the probability that a specific criterion is met or exceeded anywhere within a defined area. It can be used in addition to (or instead of) concepts such as averages and minimum and maximum levels. Lighting criteria to which this technique may be applied include luminance, illuminance, visual comfort probability (VCP), contrast, visibility metrics, and visual performance metrics.

The criterion rating assumes the name of the criterion being rated. For example, the criterion rating for illuminance is called the illuminance rating; for VCP, the VCP rating. Assume, for example, that an illuminance of 500 lx has been established as the design criterion for a space. The illuminance rating defines the likelihood that the illuminance is equal to or greater than 500 lx at any point on the workplane. This criterion rating is determined by evaluating the appropriate quantity (by calculation or measurement) at a grid of points covering the area in question. The distance between evaluation points must not exceed one-fifth the distance from any luminaire to the evaluation plane. The percentage of points that comply with the criterion is the criterion rating:

criterion rating =

$$\frac{(\text{number of points satisfying criterion}) \times 100\%}{\text{number of points computed or measured}} \quad (9-32)$$

Criterion ratings may be expressed using a notation that lists the rating, in percent, followed by the criterion, separated by the symbol @, which stands for "at." For example, a lighting system producing a luminance of 20 cd/m² over 60% of the specified area may have its luminance rating expressed as 60% @ 20 cd/m². For dimensionless criteria, such as contrast and VCP, the shorthand form for the criterion rating must include the name and value of the criteria; for example, 92% @ 70 VCP means 92% of the area has a VCP of 70 or better. The designer determines the desired coverage area for a particular criterion value.

As an example of the use of the criterion rating technique (using the foot as the unit of length), consider a square room 30 ft on a side, as shown in Figure 9-20, with an 8-ft ceiling

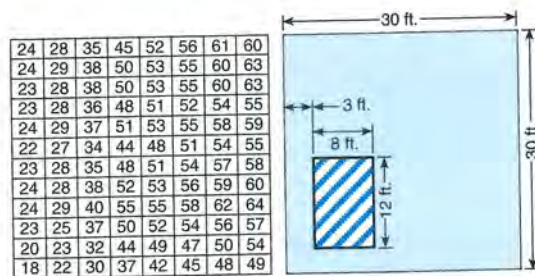


Figure 9-20. Example of criterion rating technique. The numbers in the grid represent the calculated illuminances, in fc, in the center of each ft² of the shaded portion of the work plane.

height, a 3-ft-high workplane, and recessed luminaires. The tabulated values in Figure 9-20 are calculated illuminances in the 8×12-ft shaded area. The required illuminance is 50 fc in the shaded area. The distance from the workplane to the luminaires is 5 ft (8 ft-3 ft). Thus, the distance between rows and columns of analysis points must be no greater than 1 ft (5 ft/5). To determine the criterion rating, the calculated illuminance values are examined for criterion compliance. It is found that 47 of the 96 locations receive an illuminance of 50 fc or more. The illuminance rating of this lighting system for the shaded area is then 48.9% [(47/96)×100%]. This can be expressed as 48.9% @ 50 fc.

CALCULATION OF BASIC QUANTITIES

Illuminance

Illuminance is one of the fundamental quantities used in designing and evaluating lighting systems. To determine the direct illuminance at a point on an area, one must determine that either a point or an area source method is applicable to the situation. To obtain the total illuminance at any point or on any surface, the interreflected component must be appropriately determined and added to the direct component (see Examples 2, 3, and 4 in the section "Examples of Basic Lighting Calculations," in this chapter).

Luminance

As a primary visual stimulus, luminance is the most important and useful calculated quantity. One of the most common situations in which luminance must be calculated is for the evaluation of visual tasks, such as for print on paper. Methods for evaluating the visual performance or visibility of a task require a value for the task contrast, size and adaptation luminance. The luminances of both the task (L_t) and the background (L_b) are needed to determine the task contrast. The quantities L_t and L_b are specific to a particular task location, lighting condition, and viewer orientation (see Exam-

ples 6 and 7 in the section Examples of Basic Lighting Calculations, in this chapter).

Luminance calculations are performed whenever it is necessary to calculate the luminance of a surface that exhibits a directionally sensitive reflectance. A calculation model that computes luminance should be able to predict the luminance at any point. Although it is not required that any given method be able to take all possible ranges of the following nine parameters into account, any restrictions that the method imposes should be adequately noted. Because of the complexity involved in calculating luminance, this calculation is generally performed on a computer.

- Room size and shape
- Room surface reflectances
- Luminaire characteristics
- Number and location of luminaires
- Nature of the given surface
- Observer location, line of sight, and viewing angle
- Nature and luminance of all other surfaces in the environment
- Body shadow effects
- Polarization effects

The luminance at a particular location in a luminous environment is given by

$$L = \int dE(\theta, \psi) f_r(\theta, \psi) \quad (9-33)$$

where

L = luminance at a point on a surface in a particular viewing direction,

θ, ψ = spherical coordinates, declination, and azimuth, respectively,

$dE(\theta, \psi)$ = differential amount of illuminance at the point in the plane of the surface from a direction indicated by (θ, ψ) ,

$f_r(\theta, \psi)$ = bidirectional reflectance distribution function (BRDF) of the surface material for a particular viewing direction.

Figure 9-21 indicates the necessary coordinates. This expression represents the total effect of all components of illuminance multiplied by the appropriate BRDF to give the luminance of the surface. The BRDF is dependent on the surface reflectance characteristics, the viewing angle, and the size of the light source used to measure it.

It should be noted that unlike perfectly diffuse reflectances, the BRDF is sensitive to both incident light and viewing directions. This can be expressed as

$$f_r(\theta_v, \psi_v; \theta_i, \psi_i)$$

where the subscript i represents the incident direction and subscript v the viewing direction. In many cases only the dif-

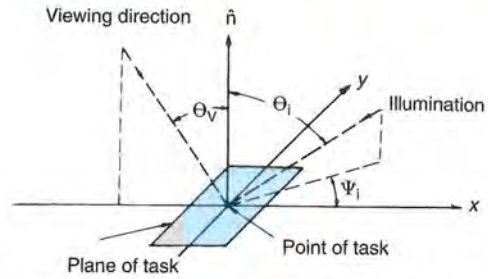


Figure 9-21. Task and illumination coordinates.

ference in azimuthal angle between the incident and exitant directions is required. Then the specification of the BRDF becomes

$$f_r(\theta_v; \theta_i, \psi_i)$$

where ψ_i is the difference in azimuthal angle between the incident and exitant directions. This simplification is not possible for non-axially-isotropic materials such as brushed metal surfaces. In such cases, the azimuthal incident and viewing angles cannot be made relative but must have a fixed orientation with respect to the surface. For many surfaces, however, the simplification can be made and the equation for luminance becomes

$$L(\theta_v) = \int dE(\theta_i, \psi_i) f_r(\theta_v; \theta_i, \psi_i) \quad (9-34)$$

The viewing angle θ_v is normally held constant.

Some surfaces exhibit sensitivity to polarization. It is then possible to separate the BRDF into two orthogonal components associated with orthogonal planes of polarization (p_1 and p_2). The BRDFs are

$$f_{rp1}(\theta_v; \theta_i, \psi_i)$$

$$f_{rp2}(\theta_v; \theta_i, \psi_i)$$

In a complementary fashion, two orthogonal components of the illuminance can be considered separately, and are indicated by dE_{p1} and dE_{p2} . This gives

$$L(\theta_v) = \int [dE_{p1}(\theta_i, \psi_i) f_{rp1}(\theta_v; \theta_i, \psi_i) + dE_{p2}(\theta_i, \psi_i) f_{rp2}(\theta_v; \theta_i, \psi_i)] \quad (9-35)$$

The expression for L is general and applicable to all situations. Since the illuminance values and luminance factors must be expressed as analytic functions in order to attempt integration of these expressions, there can be, in general, no closed-form analytic expression for L . Approximation by the method of finite elements allows an evaluation of the equation. The BRDFs now take the form of a set of discrete val-

ues that sample the continuous BRDF. The resulting approximation is

$$L(\theta_v) \approx \sum [\Delta E_{p1}(\theta_i, \psi_i) f_{rp1}(\theta_v; \theta_i, \psi_i) + \Delta E_{p2}(\theta_i, \psi_i) f_{rp2}(\theta_v; \theta_i, \psi_i)] \quad (9-36)$$

The sum is taken over all the discrete values of illuminance. The number of discrete steps determines the accuracy of the approximation. The step size in these approximations is determined by the need to model high gradients of either the illuminance or the BRDFs. In the case of calculations of luminance for visual tasks, a modification can be applied to the BRDF to take account of a body shadow.

Exitance

If room surfaces are considered to be lambertian, then the exitances of discrete elements can be found using a flux transfer model described above. Exitance distributions across a room surface can be determined at an array of points that cover it, using lighting analysis software. For rooms with a uniform lighting system, average room surface exitances can be determined using the lumen method (see Example 5 in "Examples of Basic Lighting Calculations," in this chapter).

CALCULATION OF DERIVED QUANTITIES

From the photometric quantities—illuminance, luminance, and exitance—it is possible to calculate other quantities that characterize how the human visual system interprets or is affected by a visual scene. This section discusses a number of different quantities of this type and provides equations or references for use in their computation.

Contrast

Contrast represents the difference in luminance between the task detail and its background relative to the luminance of the background or the luminances in the visual scene. There are three different formulas for computing contrast, each of which providing a slightly different answer. See Chapter 3, Vision and Perception, for definitions. See also Example 7 in "Examples of Basic Lighting Calculations," in this chapter.

Visual Performance and Visibility Metrics

Relative visual performance (RVP) and equivalent sphere illumination (ESI) are metrics for the evaluation of visual performance and visibility, respectively. The calculation of these quantities requires the determination of the task and background luminances (to obtain the task contrast). The

task size and adaptation luminance are also needed. The equations needed to compute these quantities are provided in the references for Chapter 3, Vision and Perception, where they are discussed in more detail.

Visual Comfort Probability (VCP)

Discomfort glare is the sensation of discomfort caused by luminances that are high relative to the average luminance in the field of view. The visual comfort probability (VCP) is the probability that a normal observer does not experience discomfort when viewing a lighting system under defined conditions.

Equations for the calculation of the VCP are derived from correlating photometric and geometric characteristics of simple lighting patterns with discomfort glare assessments of observers.⁶¹⁻⁶⁸ Experiments in simulated rooms have been used to confirm the extension from the laboratory to actual lighting installations.^{69,70} This system was tested and validated using lensed direct fluorescent systems only. VCP should not be applied to very small sources such as incandescent and high-intensity discharge luminaires, to very large sources such as ceiling and indirect systems, or to nonuniform sources such as parabolic reflectors.

To calculate the VCP⁷¹⁻⁸¹ several intermediate calculations must first be performed. The position index of a source, P , is an inverse measure of the relative sensitivity to a glare source at different positions throughout the field of view. Selected values or families of curves were published in early references. P is given by the formula⁷⁹

$$P = \exp[(35.2 - 0.31889\alpha - 1.22e^{-2\alpha/9})10^{-3}\beta + (21 + 0.26667\alpha - 0.002963\alpha^2)10^{-5}\beta^2] \quad (9-40)$$

where

α = angle from vertical of the plane containing the source and the line of sight (Figure 9-22), in degrees,

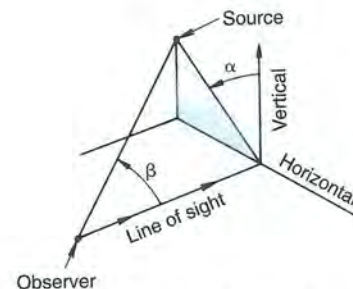


Figure 9-22. Geometry defining position index as used in VCP calculations.

β = angle between the line of sight and the line from the observer to the source.

The average luminance for the entire field of view, F_v , is approximated by the following equation:

$$F_v = L_w \omega_w + L_f \omega_f + L_c \omega_c + \sum L_s \omega_s \quad (9-41)$$

where

L_w = average luminance of the walls in cd/m^2 ,
 L_f = average luminance of the floor in cd/m^2 ,
 L_c = average luminance of the ceiling in cd/m^2 ,
 L_s = average luminance of the source in cd/m^2 ,
 ω_w = solid angle subtended at the observer by the walls in sr,
 ω_f = solid angle subtended at the observer by the floor in sr,
 ω_c = solid angle subtended at the observer by the ceiling in sr,
 ω_s = solid angle subtended at the observer by the source in sr.

The 5 in the denominator arises from the assumption that the total field of view is 5 sr .⁷⁹

A function Q has been developed for use in the calculation of the VCP. This function is given by

$$Q = 20.4 \omega_s + 1.52 \omega_s^{0.2} - 0.075 \quad (9-42)$$

where ω_s is the solid angle subtended at the observer by the source, in steradians. The values of P , F_v , and Q are used to determine the index of sensation, M :

$$M = \frac{0.50 L_s Q}{P F_v^{0.44}} \quad (9-43)$$

The luminance in the above equation is expressed in cd/m^2 . The factor 0.50 in the numerator allows for the use of these units.

From the index of sensation of each source, a discomfort glare rating (DGR) can be calculated for the full field of view. The DGR is a metric of discomfort that increases as discomfort increases; it is also used in calculating the VCP. It is given by

$$\text{DGR} = \left(\sum_{i=1}^n M_i \right)^{n^{-0.0914}} \quad (9-44)$$

where

n = number of sources in the field of view,
 M_i = index of sensation for the i th source.

The relation between DGR and VCP may be found from a graph such as Figure 9-23 or may be calculated by⁸⁰

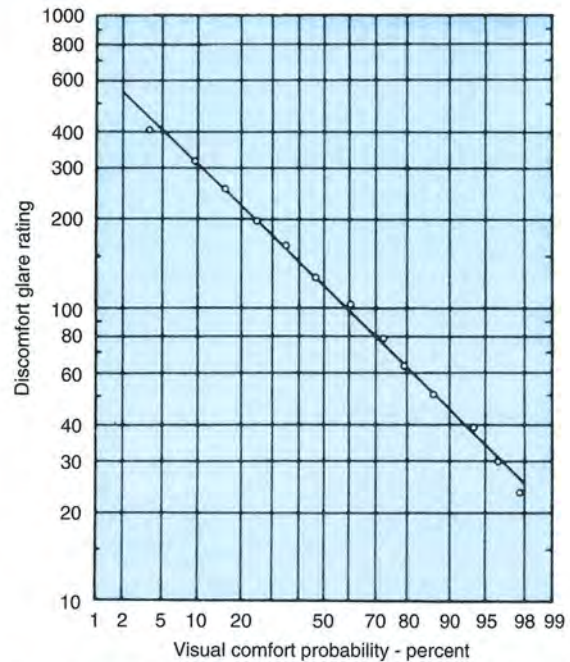


Figure 9-23. A chart for converting discomfort glare ratings (DGR) to VCP (the percentage of observers expected to judge a given lighting condition to be either comfortable or at the borderline between comfort and discomfort).

$$\text{VCP} = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374 - 1.3227 \ln \text{DGR}} e^{-t^2/2} dt \quad (9-45)$$

These basic relations may be applied through a variety of techniques. Generally, the room cavity concept is used, in which the actual ceiling and floor luminances and solid angles are replaced by their equivalent cavity values. The computation can be performed by summing throughout the enclosure.⁸¹

VCP values are frequently associated with luminaires under standardized conditions of use. In this method, the luminaires are fractionally apportioned over the ceiling according to a standard scheme. VCP values are determined for:^{71,74,76}

1. An initial average horizontal illuminance of 1000 lx (100 fc)
2. Room reflectances of $\rho_{CC} = 0.80$, $\rho_W = 0.50$, and $\rho_{FC} = 0.20$
3. Luminaire mounting heights above the floor of 2.6, 3, 4, and 4.9 m (8.5, 10, 13, and 16 ft)
4. A (given) range of room dimensions including square, long narrow, and short wide rooms
5. An observation point 1.2 m (4 ft) in front of the center of the rear wall and 1.2 m (4 ft) above the floor
6. A horizontal line of sight, directly forward

7. An upward limit to the field of view corresponding to an angle of 53° above and directly forward from the observer

There are two objectives in applying the standardized procedure. First, it simplifies calculations by permitting organization of various procedural steps. Second, it allows comparisons between those luminaires for which the standardized values have been tabulated even before a specific lighting layout has been made. Figure 9-24 illustrates a typical tabulation of visual comfort probabilities as developed by the standardized procedure.

Unified Glare Rating (UGR)

The CIE has recently developed a unified glare rating (UGR) system. This system is intended for discomfort glare prediction and is likely to be adopted by many nations. The IESNA is currently considering UGR for future recommendations. UGR is calculated from

$$\text{UGR} = 8 \log_{10} \left(\frac{0.25}{L_b} \right) \sum_i \frac{L_i^2 \omega_i}{P_i^2}$$

where

- L_b = luminance of the field of view, in cd/m^2 , not including luminaire luminance,
- L = luminance of a luminaire in the direction of the observer,
- ω = solid angle of a luminaire subtended to the observer,
- P = position index of luminaire.

This formula is limited to those situations where $0.0003 \leq \omega \leq 0.1$. Values of UGR range from 5 to 30, with higher numbers indicating greater discomfort glare.

Average Illuminance Calculation: The Lumen Method

The lumen method is used in calculating the average illuminance $\bar{E}$ on the workplane in an interior. This is defined as

$$\bar{E} = \frac{\text{total flux onto workplane}}{\text{workplane area}} \quad (9-46)$$

A coefficient of utilization (CU) gives the fraction of lamp lumens that reach the workplane, directly from sources and from interreflections. The CU takes into account the efficiency of the luminaire and the impact of the luminaire distribution and the room surfaces in its derivation. Thus the number of lumens produced by the lamps, multiplied by this CU, determines the number that reaches the workplane:

Figure 9-24. Example of a Tabulation of VCP Values

Room		Luminaires Lengthwise				Luminaires Crosswise			
W	L	8.5	10.0	13.0	16.0	8.5	10.0	13.0	16.0
20	20	78	82	90	94	77	81	89	93
20	30	73	76	82	88	72	75	81	86
20	40	71	73	78	82	70	72	76	80
20	60	69	71	74	78	68	70	73	76
30	20	78	82	88	92	77	81	87	92
30	30	73	75	80	85	72	74	79	84
30	40	70	72	75	78	69	71	74	77
30	60	68	69	71	74	67	69	70	73
30	80	67	69	69	72	67	68	68	71
40	20	79	82	87	92	79	82	87	91
40	30	74	76	79	84	73	75	78	83
40	40	71	72	74	77	70	71	73	76
40	60	68	69	70	72	68	69	69	71
40	80	67	68	68	70	67	68	67	69
40	100	67	68	67	69	67	67	66	68
60	30	75	76	79	83	74	76	78	82
60	40	71	72	74	76	71	72	73	76
60	60	69	69	69	71	68	69	68	70
60	80	68	68	67	69	67	68	66	68
60	100	67	67	66	67	67	67	65	66
100	40	74	75	75	78	74	74	75	77
100	60	71	71	71	72	71	71	70	72
100	80	70	70	68	69	70	69	67	69
100	100	69	68	66	67	69	68	66	67

This example is for use when the units of length and illuminance are the foot (ft) and footcandle (fc). VCP values are identical if units of length and illuminance are the meter (m) and the lux (lx).

Wall Reflectance, 50%; Effective Ceiling Cavity Reflectance, 80%; Effective Floor Cavity Reflectance, 20%; Luminaire No. 000; Workplane Illuminance, 100 fc

$$\bar{E}_{\text{initial}} = \frac{(\text{total lamp lumens}) \times \text{CU}}{\text{workplane area}} \quad (9-47)$$

Since the design objective usually is maintained illuminance, a light loss factor must be applied to allow for the estimated depreciation in lamp lumens over time, the estimated losses from dirt collection on the luminaire surfaces (including lamps), and other factors that affect luminaire lumen output over time. The formula thus becomes

$$\bar{E}_{\text{maintained}} = \frac{(\text{total lamp lumens}) \times \text{CU} \times \text{LLF}}{\text{workplane area}} \quad (9-48)$$

where

CU = coefficient of utilization,
LLF = light loss factor.

Although design calculations are based on the LLF using both nonrecoverable and recoverable factors, it is sometimes necessary to calculate illuminance in a new lighting installation. In such cases, repeat the calculation using the nonrecoverable losses, since the recoverable losses do not occur at 100 hours, the time at which lamps are nominally at rated lumens.

The lamp lumens in the formula are most conveniently taken as the total rated lamp lumens in the luminaires:

$$\bar{E}_{\text{maintained}} = \frac{(\text{number of luminaires}) \times (\text{lamps per luminaire}) \times (\text{lamp lumens}) \times \text{CU} \times \text{LLF}}{\text{workplane area}} \quad (9-49)$$

If the desired maintained illuminance is known, this equation can be solved for the total number of luminaires needed:

$$\begin{aligned} \text{number of luminaires} \\ = \frac{\bar{E}_{\text{maintained}} \times (\text{workplane area})}{(\text{lamps per luminaire}) \times (\text{lamp lumens}) \times \text{CU} \times \text{LLF}} \end{aligned} \quad (9-50)$$

For a typical form for calculating illuminance, see Figure 9-25.

Limitations. The illuminance computed by the lumen method is an average value that is representative only if the luminaires are spaced to obtain reasonably uniform illuminance. The calculation of the coefficients of utilization is based on empty interiors having surfaces that exhibit perfectly diffuse reflectance. The average illuminance determined by the lumen method is defined to be the total lumens reaching the workplane divided by the area of the workplane. The average value determined this way might vary considerably from that obtained by averaging discrete values of illuminance at several points.

Calculation Procedure. Figure 9-25 provides a procedure for calculating average maintained illuminance using the zonal-cavity method.⁴⁴⁻⁴⁶

Cavity Ratios. The radiative exchange between the top and the base of a rectangular space is a function of the proportions of its length, width, and height. Cavity ratio values approximate this effect by combining these proportions into a single quantity.

In the zonal-cavity method, the effects of room proportions, luminaire suspension length, and workplane height upon the coefficient of utilization are respectively represented by the room cavity ratio, ceiling cavity ratio, and floor cavity ratio. These ratios are determined by dividing the room into three cavities, as shown by Figure 9-26, and substituting dimensions (in m or ft) into the following formula:

$$\text{cavity ratio} = \frac{5h(\text{cavity length} + \text{cavity width})}{\text{cavity length} \times \text{cavity width}} \quad (9-51)$$

where

$$h = \begin{cases} h_{\text{RC}} & \text{for the room cavity ratio (RCR)} \\ h_{\text{CC}} & \text{for the ceiling cavity ratio (CCR)} \\ h_{\text{FC}} & \text{for the floor cavity ratio (FCR)} \end{cases}$$

The illuminance in rooms of irregular shape can be determined by calculating the room cavity ratio using the following formula and solving the problem in the usual manner:

$$\begin{aligned} \text{cavity ratio} \\ = \frac{2.5 \times (\text{cavity height}) \times (\text{cavity perimeter})}{\text{area of cavity base}} \end{aligned} \quad (9-52)$$

Effective Cavity Reflectances. Figure 9-27 provides a means of converting the combination of wall and ceiling or wall and floor reflectances into a single effective ceiling cavity reflectance, ρ_{CC} , and a single effective floor cavity reflectance, ρ_{FC} . In lumen method calculations, the ceiling, wall, and floor reflectances should be initial values. The RSDD factor compensates for the decrease of reflectance with time. Note that for surface-mounted and recessed luminaires, the CCR equals 0 and the actual ceiling reflectance may be used for ρ_{CC} .

A rectangular cavity consists of four walls, each having a reflectance of ρ_w , and a base of reflectance ρ_B (ceiling or floor reflectance). The effective reflectance, ρ_{eff} , of this cavity is the ratio of the flux reflected out to the flux entering the cavity through its opening. If the reflectances are assumed to be perfectly diffuse and the flux is assumed to enter the cavity in a perfectly diffuse way, it is possible to calculate the effective cavity reflectance using flux transfer theory. The result is

$$\begin{aligned} \rho_{\text{eff}} \\ = \frac{\rho_B \rho_w f \left(2 \frac{A_B}{A_w} (1-f) - f \right) + \rho_B f^2 + \rho_w \frac{A_B}{A_w} (1-f)^2}{1 - \rho_B \rho_w \frac{A_B}{A_w} (1-f)^2 - \rho_w \left(1 - 2 \frac{A_B}{A_w} (1-f) \right)} \end{aligned} \quad (9-53)$$

where

A_B, A_w = areas of the cavity base and walls, respectively,
 ρ_B, ρ_w = reflectances of the cavity base and walls, respectively,
 f = form factor between the cavity opening and the cavity base.

The form factor f in the above equation is given by

GENERAL INFORMATION

Project identification: _____
(Give name of area and/or building and room number)

Average maintained illuminance for design: _____ lux or
_____ footcandles

Lamp data:

Type and color: _____

Number per luminaire: _____

Total lumens per luminaire: _____

Luminaire data:

Manufacturer: _____

Catalog number: _____

SELECTION OF COEFFICIENT OF UTILIZATION

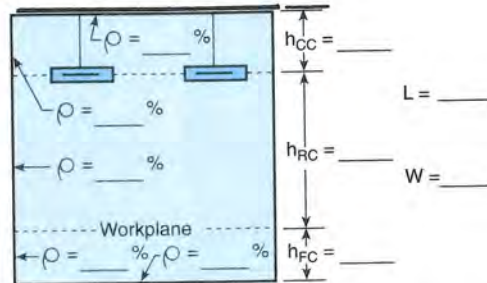
Step 1: Fill in sketch at right

Step 2: Determine Cavity Ratios

Room Cavity Ratio, RCR = _____

Ceiling Cavity Ratio, CCR = _____

Floor Cavity Ratio, FCR = _____



Step 3: Obtain Effective Ceiling Cavity Reflectance (ρ_{CC})

ρ_{CC} = _____

Step 4: Obtain Effective Floor Cavity Reflectance (ρ_{FC})

ρ_{FC} = _____

Step 5: Obtain Coefficient of Utilization (CU) from Manufacturer's Data

CU = _____

SELECTION OF LIGHT LOSS FACTORS

Nonrecoverable
Luminaire ambient temperature _____

Voltage to luminaire _____

Ballast factor _____

Luminaire surface depreciation _____

Recoverable
Room surface dirt depreciation
RSDD _____
Lamp lumen depreciation
LLD _____
Lamp burnouts factor
LBO _____
Luminaire dirt depreciation
LDD _____

Total light loss factor, LLF (product of individual factors above) = _____

CALCULATIONS

(Average Maintained Illuminance)

$$\text{Number of Luminaires} = \frac{(\text{Illuminance}) \times (\text{Area})}{(\text{Lumens per Luminaire}) \times (\text{CU}) \times (\text{LLF})}$$

$$= \frac{\text{_____}}{\text{_____}} = \text{_____}$$

$$\text{Illuminance} = \frac{(\text{Number of Luminaires}) \times (\text{Lumens per Luminaire}) \times (\text{CU}) \times (\text{LLF})}{(\text{Area})}$$

$$= \frac{\text{_____}}{\text{_____}} = \text{_____}$$

Calculated by: _____ Date: _____

Figure 9-25. Average illuminance calculation sheet.

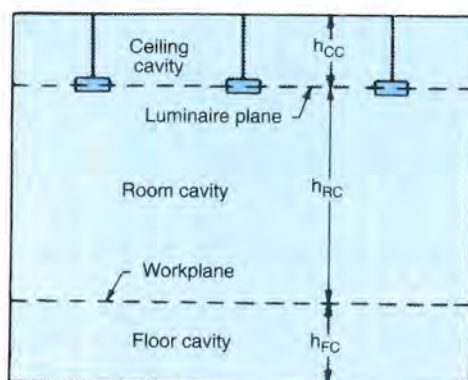


Figure 9-26. The three cavities used in the zonal-cavity method.

$$\begin{aligned}
 f = & \frac{2}{\pi xy} \ln \left(\frac{(1+x^2)(1+y^2)}{1+x^2+y^2} \right)^{1/2} \\
 & + \frac{2}{\pi x} (1+x^2)^{1/2} \arctan \left(\frac{y}{(1+x^2)^{1/2}} \right) \\
 & + \frac{2}{\pi y} (1+y^2)^{1/2} \arctan \left(\frac{x}{(1+y^2)^{1/2}} \right) \\
 & - \frac{2}{\pi x} \arctan y - \frac{2}{\pi y} \arctan x
 \end{aligned} \quad (9-54)$$

where x and y have the following values:

$$x = \frac{\text{cavity length}}{\text{cavity depth}} \quad (9-55a)$$

$$y = \frac{\text{cavity length}}{\text{cavity depth}} \quad (9-55b)$$

The arctangents are expressed in radians. If it is assumed that the cavity is square, then

$$x = y = \frac{10}{\text{cavity ratio}} \quad (9-56)$$

The effective ceiling cavity reflectance of nonhorizontal ceilings can be determined by the following formula. The illuminance problem is then solved in the usual manner:

$$\rho_{CC} = \frac{\rho}{\frac{A_s}{A_o} - \rho \left(\frac{A_s}{A_o} - 1 \right)} \quad (9-57)$$

where

A_o = area of the ceiling opening,

A_s = area of the ceiling surface,

ρ = reflectance of the ceiling surface.

The formula for ρ_{CC} applies to concave ceilings such as a hemispherical dome where all parts of the ceiling are exposed to all other parts. If the ceiling surface reflectance is not the same for all parts of the ceiling, an area-weighted average should be used. Thus, if the ceiling has n sections, then

$$\rho = \frac{\sum_{i=1}^n \rho_i A_i}{\sum_{i=1}^n A_i} \quad (9-58)$$

where

ρ_i = reflectance of the i th section of the ceiling,

A_i = area of the i th section of the ceiling.

Luminaire Coefficients of Utilization. Absorption of light in a luminaire is taken into account in the computation of coefficient of utilization (CU) for that luminaire. Figure 9-28 is a tabulation of coefficients of utilization calculated by the zonal-cavity method for representative luminaire types. These coefficients are for an effective floor cavity reflectance of 20%, but any CU obtained from the table may be corrected for a different value of ρ_{FC} by applying the appropriate multiplier from Figure 9-29.

Figure 9-28 is based on generic luminaires that can be readily identified. As an example, there are many variations of the flat-bottom fluorescent troffer using prismatic lenses. The luminaires in Figure 9-28 are not to be considered as recommended luminaires. The entries for some present useful data even though the luminaires concerned are no longer commonly used. For example, luminaire 2 is largely out of use; however, the coefficients apply to any indirect luminaire of similar efficiency and direct component, since they do not depend on the shape of the upward intensity distribution. An important feature of these coefficients is that the performance of luminaires of similar distributions but different efficiencies may also be analyzed with their use by making a simple multiplicative correction (see note 3 of Figure 9-28).

Since the light loss factor includes the effect of dirt deposited on wall surfaces, the selection of the proper column of wall reflectances, ρ_w , should be based on the initial values expected. The wall reflectance should also represent the weighted average of the reflectances of the painted areas, fenestration or daylight controls, chalkboards, shelves, and so forth in the area to be lighted. The weighting should be based on the relative areas of each type of surface within the cavity being considered. In using Figure 9-29, it is often necessary to interpolate between room cavity ratios and effective ceiling cavity reflectances. This is most easily accomplished by interpolating first between RCRs to obtain CUs for effective ceiling cavity reflectances that straddle the actual ρ_{CC} , and then interpolating between these CUs.

Instructions and Notes: Tables of Coefficients of Utilization (Figure 9-28)

1. The luminaires in this table are organized by source type and luminaire form rather than by application, for convenience in locating luminaires. In some cases, the data are based on an actual luminaire; in other cases, they represent a composite of generic luminaire types. Therefore, whenever possible, specific luminaire data should be used in preference to those in this table.
2. The polar intensity sketch (intensity distribution curve) and the corresponding luminaire spacing criterion are representative of many luminaires of each type shown. A specific luminaire may differ in perpendicular-plane (crosswise) and parallel-plane (lengthwise) intensity distributions and in spacing criterion from the values shown. However, the various coefficients depend only on the average intensity at each polar angle from nadir. The average intensity values used to generate the coefficients are given at the end of the table, normalized to 1000 lamp lumens for reference.
3. The various coefficients depend only on the average intensity distribution curve and are linearly related to the total luminaire efficiency. Consequently, the tabulated coefficients can be applied to luminaires with similarly shaped average intensity distributions along with a correcting multiplier equal to the new luminaire total efficiency divided by the tabulated luminaire total efficiency. The use of polarizing lenses on fluorescent luminaires has no effect on the coefficients given in this table except as they affect the total luminaire efficiency.
4. Satisfactory installations depend on many factors, including the environment, space utilization, and luminous criteria, as well as the luminaire itself. Consequently, a definitive spacing recommendation cannot be assigned to the luminaire as such. The spacing criterion (SC) values given are only general guides. SC values are not assigned to semi-indirect and indirect luminaires, since the basis of this technique does not apply to such situations. Also, SC values are not given for those bat-wing luminaires that must be located by criteria other than that of horizontal illuminance.
5. Key:
 - ρ_{CC} = ceiling cavity reflectance (percent),
 - ρ_W = wall reflectance (percent),
 - ρ_{FC} = floor cavity reflectance (percent),
 - RCR = room cavity ratio,
 - WDRC = wall direct radiation coefficient,
 - SC = luminaire spacing criterion,
 - NA = not applicable.

6. Many of the luminaires in this figure appeared in earlier editions of the IESNA *Lighting Handbook*. The identifying number may be different due to a reordering of the luminaires. In some cases, the data have been modified in view of more recent or more extensive information. The user should specifically refer to this edition of the *Lighting Handbook* when referencing luminaires.
7. Fluorescent lamp luminaire efficiencies, and consequently the coefficients, are a function of the number of lamps in relation to the size of the luminaire. This is due to temperature changes and to changes in the blocking of light. In this figure, fluorescent lamp luminaires have been chosen with typical luminaire sizes and numbers of lamps; these are identified under the typical luminaire drawings. Variations of the coefficients with size and number of lamps depend on the many details of luminaire construction. The following correction factors are average values to apply to a four-lamp luminaire 610 mm (2 ft) wide:

No. of lamps	Width, mm	Width, ft	Multiply by
8	1220	4	1.05
3	610	2	1.05
2	610	2	1.1
2	300	1	0.9

Multiply the entries for two-lamp wraparound luminaires by 0.95 for four lamps.

8. Photometric data for fluorescent lamp luminaires in this table are based on tests using standard-wattage fluorescent lamps. Reduced-wattage fluorescent lamps cause lower lamp operating temperatures with some luminaires. Consequently, the efficiency and coefficients may be slightly increased. It is desirable to obtain specific correction factors from the manufacturers. Typical factors for reduced-wattage fluorescent lamps (approximately 10% below standard lamp wattages) are as follows:

Luminaire	Multiply by
2-lamp strip, surface mounted	1.03
4-lamp troffer, enclosed, non-air-handling	1.07
4-lamp wraparound, surface mounted	1.07
2-lamp industrial, vented	1.00

Electronic ballasts can be designed for any arbitrary operating condition. The manufacturer must be consulted for specific data.

Figure 9-28 Coefficients of Utilization for Typical Luminaires

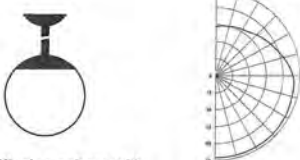
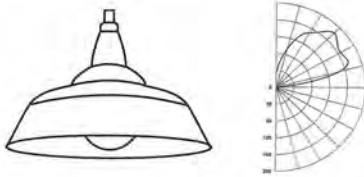
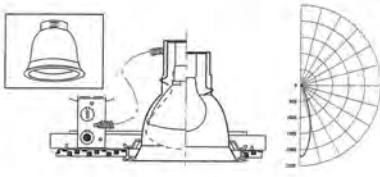
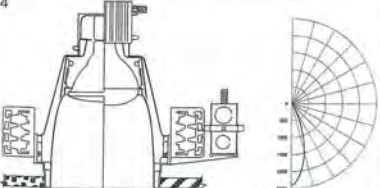
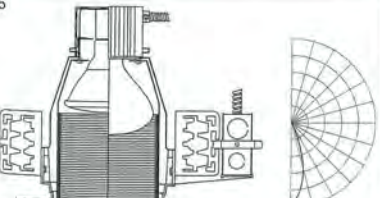
Typical Luminaire	Typical Intensity Distribution	$\rho_{cc} \rightarrow$			80			70			50			30			10			0
		$\rho_w \rightarrow$			70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR $\downarrow$			Lamp = 150A211F SC (along, across, 45°) = 1.5, 1.5, 1.5															
1		0	0.87	0.87	0.87	0.81	0.81	0.81	0.70	0.70	0.70	0.59	0.59	0.59	0.49	0.49	0.49	0.45	0.45	0.45
		1	0.76	0.71	0.66	0.70	0.66	0.61	0.56	0.52	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30	0.30	0.30
		2	0.68	0.60	0.53	0.62	0.55	0.50	0.47	0.42	0.38	0.39	0.35	0.32	0.31	0.29	0.26	0.23	0.23	0.23
		3	0.61	0.52	0.44	0.56	0.48	0.41	0.40	0.35	0.31	0.33	0.29	0.26	0.27	0.24	0.21	0.18	0.18	0.18
		4	0.55	0.45	0.37	0.51	0.42	0.35	0.35	0.30	0.25	0.29	0.25	0.21	0.23	0.20	0.17	0.14	0.14	0.14
		5	0.51	0.40	0.32	0.46	0.37	0.30	0.31	0.25	0.21	0.26	0.21	0.18	0.21	0.17	0.14	0.12	0.12	0.12
		6	0.46	0.35	0.28	0.42	0.33	0.26	0.28	0.22	0.18	0.23	0.19	0.15	0.19	0.15	0.12	0.10	0.10	0.10
		7	0.43	0.32	0.25	0.39	0.29	0.23	0.25	0.20	0.16	0.21	0.16	0.13	0.17	0.13	0.11	0.09	0.09	0.09
		8	0.40	0.29	0.22	0.36	0.27	0.20	0.23	0.17	0.14	0.19	0.15	0.12	0.15	0.12	0.09	0.07	0.07	0.07
		9	0.37	0.26	0.19	0.34	0.24	0.18	0.21	0.16	0.12	0.17	0.13	0.10	0.14	0.11	0.08	0.07	0.07	0.07
		10	0.34	0.24	0.17	0.32	0.22	0.16	0.19	0.14	0.11	0.16	0.12	0.09	0.13	0.10	0.08	0.06	0.06	0.06
2		EFF = 86.5%			% DN = 4.0%			% UP = 96.0%			Lamp = 100A21/5B SC (along, across, 45°) = N/A, N/A, N/A									
		0	0.99	0.99	0.99	0.97	0.97	0.97	0.93	0.93	0.93	0.89	0.89	0.89	0.85	0.85	0.85	0.83	0.83	0.83
		1	0.91	0.87	0.84	0.89	0.85	0.82	0.82	0.79	0.77	0.79	0.76	0.74	0.76	0.74	0.72	0.71	0.71	0.71
		2	0.83	0.76	0.70	0.80	0.74	0.69	0.71	0.67	0.63	0.69	0.65	0.62	0.66	0.63	0.60	0.59	0.59	0.59
		3	0.75	0.66	0.59	0.73	0.65	0.59	0.62	0.57	0.53	0.60	0.55	0.52	0.58	0.54	0.51	0.49	0.49	0.49
		4	0.69	0.58	0.51	0.67	0.57	0.50	0.55	0.49	0.44	0.53	0.48	0.44	0.51	0.47	0.43	0.41	0.41	0.41
		5	0.63	0.52	0.44	0.61	0.51	0.44	0.49	0.43	0.38	0.47	0.42	0.37	0.46	0.41	0.37	0.35	0.35	0.35
		6	0.58	0.46	0.39	0.56	0.46	0.38	0.44	0.38	0.33	0.43	0.37	0.33	0.41	0.36	0.32	0.31	0.31	0.31
		7	0.53	0.42	0.34	0.52	0.41	0.34	0.40	0.33	0.29	0.39	0.33	0.29	0.38	0.32	0.28	0.27	0.27	0.27
		8	0.50	0.38	0.31	0.48	0.37	0.31	0.36	0.30	0.26	0.35	0.30	0.25	0.34	0.29	0.25	0.24	0.24	0.24
		9	0.46	0.35	0.28	0.45	0.34	0.28	0.33	0.27	0.23	0.32	0.27	0.23	0.32	0.26	0.23	0.21	0.21	0.21
		10	0.43	0.32	0.25	0.42	0.32	0.25	0.31	0.25	0.21	0.30	0.24	0.21	0.29	0.24	0.20	0.19	0.19	0.19
3		EFF = 100%			% DN = 100%			% UP = 0%			Lamp = 150PAR38FL SC (along, across, 45°) = 0.6, 0.6, 0.6									
		0	1.20	1.20	1.20	1.17	1.17	1.17	1.12	1.12	1.12	1.07	1.07	1.07	1.03	1.03	1.03	1.00	1.00	1.00
		1	1.14	1.11	1.08	1.11	1.08	1.06	1.04	1.02	1.00	1.01	0.99	0.97	0.97	0.96	0.95	0.93	0.93	0.93
		2	1.08	1.02	0.98	1.05	1.01	0.97	0.97	0.94	0.91	0.94	0.92	0.89	0.92	0.89	0.87	0.86	0.86	0.86
		3	1.02	0.95	0.90	1.00	0.94	0.89	0.91	0.87	0.84	0.89	0.85	0.82	0.86	0.84	0.81	0.79	0.79	0.79
		4	0.97	0.89	0.83	0.95	0.88	0.83	0.86	0.81	0.78	0.84	0.80	0.77	0.82	0.79	0.76	0.74	0.74	0.74
		5	0.92	0.84	0.78	0.91	0.83	0.77	0.81	0.76	0.72	0.79	0.75	0.72	0.78	0.74	0.71	0.70	0.70	0.70
		6	0.88	0.79	0.73	0.87	0.78	0.73	0.77	0.72	0.68	0.75	0.71	0.68	0.74	0.70	0.67	0.66	0.66	0.66
		7	0.84	0.75	0.69	0.83	0.74	0.69	0.72	0.68	0.64	0.72	0.67	0.64	0.71	0.67	0.64	0.62	0.62	0.62
		8	0.81	0.71	0.66	0.80	0.71	0.65	0.70	0.65	0.61	0.69	0.64	0.61	0.68	0.64	0.61	0.59	0.59	0.59
		9	0.78	0.68	0.62	0.77	0.68	0.62	0.67	0.62	0.58	0.66	0.61	0.58	0.65	0.61	0.58	0.57	0.57	0.57
		10	0.75	0.65	0.60	0.74	0.65	0.59	0.64	0.59	0.56	0.63	0.59	0.56	0.63	0.58	0.55	0.54	0.54	0.54
4		EFF = 66.2%			% DN = 100			% UP = 0			Lamp = 150PAR38FL* SC (along, across, 45°) = 0.6, 0.6, 0.6									
		0	1.10	1.10	1.10	1.07	1.07	1.07	1.02	1.02	1.02	0.98	0.98	0.98	0.94	0.94	0.94	0.92	0.92	0.92
		1	1.06	1.03	1.02	1.03	1.01	1.00	0.98	0.96	0.95	0.94	0.93	0.92	0.91	0.90	0.90	0.88	0.88	0.88
		2	1.02	0.98	0.95	1.00	0.96	0.94	0.94	0.91	0.89	0.91	0.89	0.88	0.88	0.87	0.86	0.84	0.84	0.84
		3	0.98	0.93	0.90	0.96	0.92	0.89	0.90	0.87	0.85	0.88	0.85	0.83	0.86	0.84	0.82	0.81	0.81	0.81
		4	0.94	0.89	0.85	0.93	0.88	0.84	0.86	0.83	0.80	0.84	0.82	0.79	0.83	0.81	0.79	0.77	0.77	0.77
		5	0.91	0.85	0.81	0.90	0.84	0.80	0.83	0.79	0.77	0.81	0.78	0.76	0.80	0.77	0.75	0.74	0.74	0.74
		6	0.88	0.81	0.77	0.87	0.81	0.77	0.80	0.76	0.73	0.78	0.75	0.73	0.77	0.75	0.72	0.71	0.71	0.71
		7	0.85	0.78	0.74	0.84	0.78	0.74	0.77	0.73	0.70	0.76	0.72	0.70	0.75	0.72	0.70	0.69	0.69	0.69
		8	0.82	0.75	0.71	0.81	0.75	0.71	0.74	0.70	0.68	0.73	0.70	0.67	0.72	0.69	0.67	0.66	0.66	0.66
		9	0.79	0.72	0.68	0.78	0.72	0.68	0.71	0.68	0.65	0.70	0.67	0.65	0.70	0.67	0.65	0.64	0.64	0.64
		10	0.77	0.70	0.66	0.76	0.69	0.65	0.69	0.65	0.63	0.68	0.65	0.62	0.68	0.65	0.62	0.61	0.61	0.61
5		EFF = 66.2%			% DN = 100			% UP = 0			Lamp = 150PAR38FL* SC (along, across, 45°) = 0.6, 0.6, 0.6									
		0	0.79	0.79	0.79	0.77	0.77	0.77	0.74	0.74	0.74	0.70	0.70	0.70	0.68	0.68	0.68	0.66	0.66	0.66
		1	0.76	0.75	0.73	0.75	0.73	0.72	0.71	0.70	0.69	0.68	0.68	0.67	0.66	0.66	0.65	0.64	0.64	0.64
		2	0.74	0.71	0.69	0.72	0.70	0.68	0.68	0.67	0.65	0.66	0.65	0.64	0.64	0.63	0.63	0.62	0.62	0.62
		3	0.71	0.68	0.66	0.70	0.67	0.65	0.66	0.64	0.62	0.64	0.63	0.61	0.63	0.61	0.60	0.60	0.60	0.60
		4	0.69	0.65	0.63	0.68	0.65	0.62	0.63	0.61	0.60	0.62	0.60	0.59	0.61	0.60	0.58	0.58	0.58	0.58
		5	0.67	0.63	0.60	0.66	0.62	0.60	0.61	0.59	0.57	0.60	0.58	0.57	0.59	0.58	0.56	0.56	0.56	0.56
		6	0.65	0.61	0.58	0.64	0.60	0.58	0.59	0.57	0.55	0.59	0.57	0.55	0.58	0.56	0.55	0.54	0.54	0.54
		7	0.63	0.59	0.56	0.62	0.58	0.56	0.57	0.55	0.53	0.57	0.55	0.53	0.56	0.54	0.53	0.52	0.52	0.52
		8	0.61	0.57	0.54	0.60	0.56	0.54	0.56	0.53	0.52	0.55	0.53	0.52	0.55	0.53	0.51	0.51	0.51	0.51
		9	0.59	0.55	0.52	0.59	0.55	0.52	0.54	0.52	0.50	0.54	0.51	0.50	0.53	0.51	0.50	0.49	0.49	0.49
		10	0.58	0.53	0.51	0.57	0.53	0.50	0.53	0.50	0.49	0.52	0.50	0.48	0.52	0.50	0.48	0.48	0.48	0.48

Figure 9-28 Continued

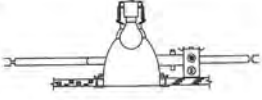
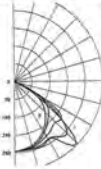
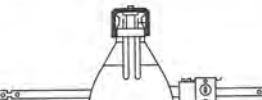
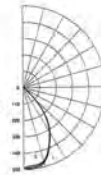
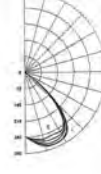
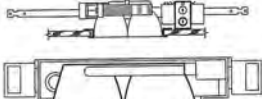
Typical Luminaire	Typical Intensity Distribution	Typical Intensity Distribution																			
		pcc →			80			70			50			30			10			0	
		ρw →			70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0	
		RCR ↓	Lamp = 150A211F SC (along, across, 45°) = 1.2, 1.2, 1.1																		
			EFF = 96.2%	% DN = 100%						% UP = 0%											
 A-lamp downlight with spec. anodized reflector		0	0.82	0.82	0.82	0.81	0.81	0.81	0.77	0.77	0.77	0.74	0.74	0.74	0.71	0.71	0.71	0.69			
		1	0.78	0.76	0.75	0.77	0.75	0.73	0.72	0.71	0.70	0.70	0.68	0.68	0.67	0.66	0.66	0.64			
		2	0.74	0.71	0.68	0.73	0.70	0.67	0.67	0.65	0.63	0.65	0.63	0.62	0.63	0.62	0.61	0.59			
		3	0.70	0.66	0.62	0.69	0.65	0.61	0.63	0.60	0.58	0.61	0.59	0.57	0.59	0.57	0.56	0.55			
		4	0.66	0.61	0.57	0.65	0.60	0.56	0.58	0.55	0.53	0.57	0.54	0.52	0.56	0.53	0.51	0.50			
		5	0.63	0.56	0.52	0.61	0.56	0.52	0.55	0.51	0.48	0.53	0.50	0.48	0.52	0.50	0.48	0.46			
		6	0.59	0.53	0.48	0.58	0.52	0.48	0.51	0.47	0.45	0.50	0.47	0.44	0.49	0.46	0.44	0.43			
		7	0.56	0.49	0.45	0.55	0.49	0.44	0.48	0.44	0.41	0.47	0.43	0.41	0.46	0.43	0.41	0.40			
		8	0.53	0.46	0.41	0.52	0.45	0.41	0.45	0.41	0.38	0.44	0.40	0.38	0.43	0.40	0.38	0.37			
		9	0.50	0.43	0.39	0.49	0.43	0.38	0.42	0.38	0.35	0.41	0.38	0.35	0.41	0.37	0.35	0.34			
		10	0.47	0.40	0.36	0.47	0.40	0.36	0.39	0.36	0.33	0.39	0.35	0.33	0.38	0.35	0.33	0.32			
 8" Open reflector downlight (32W CFL)		Lamp = CF6/32 SC (along, across, 45°) = 1.1, 1.1, 1.1																			
		0	0.77	0.77	0.77	0.75	0.75	0.75	0.72	0.72	0.72	0.69	0.69	0.69	0.66	0.66	0.66	0.65			
		1	0.73	0.72	0.70	0.72	0.70	0.69	0.67	0.66	0.65	0.65	0.64	0.63	0.63	0.62	0.61	0.60			
		2	0.69	0.66	0.63	0.68	0.65	0.62	0.63	0.61	0.59	0.61	0.59	0.58	0.59	0.58	0.57	0.55			
		3	0.66	0.61	0.58	0.64	0.60	0.57	0.59	0.56	0.54	0.57	0.55	0.53	0.55	0.54	0.52	0.51			
		4	0.62	0.57	0.53	0.61	0.56	0.52	0.55	0.51	0.49	0.53	0.51	0.48	0.52	0.50	0.48	0.47			
		5	0.58	0.53	0.49	0.57	0.52	0.48	0.51	0.48	0.45	0.50	0.47	0.45	0.49	0.46	0.44	0.43			
		6	0.55	0.49	0.45	0.54	0.48	0.45	0.47	0.44	0.41	0.46	0.43	0.41	0.46	0.43	0.41	0.40			
		7	0.52	0.46	0.41	0.51	0.45	0.41	0.44	0.41	0.38	0.44	0.40	0.38	0.43	0.40	0.38	0.37			
		8	0.49	0.43	0.38	0.48	0.42	0.38	0.42	0.38	0.35	0.41	0.38	0.35	0.40	0.37	0.35	0.34			
		9	0.47	0.40	0.36	0.46	0.40	0.36	0.39	0.35	0.33	0.38	0.35	0.33	0.38	0.35	0.33	0.32			
10	0.44	0.37	0.33	0.44	0.37	0.33	0.37	0.33	0.31	0.36	0.33	0.30	0.36	0.33	0.30	0.29					
 8" Open reflector downlight (2-26W CFL)		Lamp = (2) CFQ26 SC (along, across, 45°) = 1.5, 1.6, 1.5																			
		0	0.73	0.73	0.73	0.72	0.72	0.72	0.68	0.68	0.68	0.66	0.66	0.66	0.63	0.63	0.63	0.62			
		1	0.69	0.67	0.66	0.68	0.66	0.64	0.63	0.62	0.61	0.61	0.60	0.59	0.59	0.58	0.57	0.56			
		2	0.65	0.61	0.59	0.64	0.60	0.58	0.58	0.56	0.54	0.56	0.55	0.53	0.55	0.53	0.52	0.51			
		3	0.61	0.56	0.52	0.59	0.55	0.52	0.53	0.51	0.48	0.52	0.49	0.47	0.50	0.48	0.47	0.46			
		4	0.57	0.51	0.47	0.56	0.50	0.47	0.49	0.46	0.43	0.48	0.45	0.43	0.47	0.44	0.42	0.41			
		5	0.53	0.47	0.42	0.52	0.46	0.42	0.45	0.41	0.39	0.44	0.41	0.38	0.43	0.40	0.38	0.37			
		6	0.50	0.43	0.38	0.48	0.42	0.38	0.41	0.38	0.35	0.40	0.37	0.35	0.40	0.37	0.34	0.33			
		7	0.46	0.39	0.35	0.45	0.39	0.35	0.38	0.34	0.31	0.37	0.34	0.31	0.36	0.33	0.31	0.30			
		8	0.43	0.36	0.32	0.42	0.36	0.32	0.35	0.31	0.29	0.34	0.31	0.28	0.34	0.31	0.28	0.27			
		9	0.41	0.33	0.29	0.40	0.33	0.29	0.33	0.29	0.26	0.32	0.28	0.26	0.31	0.28	0.26	0.25			
10	0.38	0.31	0.27	0.37	0.31	0.27	0.30	0.26	0.24	0.30	0.26	0.24	0.29	0.26	0.24	0.23					
 8" Round with cross baffles		Lamp = (2) CFQ26 SC (along, across, 45°) = 1.2, 1.2, 1.1																			
		0	0.47	0.47	0.47	0.46	0.46	0.46	0.44	0.44	0.44	0.42	0.42	0.42	0.41	0.41	0.41	0.40			
		1	0.45	0.44	0.43	0.44	0.43	0.42	0.41	0.41	0.40	0.40	0.39	0.39	0.39	0.38	0.38	0.37			
		2	0.43	0.41	0.39	0.42	0.40	0.38	0.39	0.37	0.36	0.37	0.36	0.35	0.36	0.35	0.35	0.34			
		3	0.40	0.37	0.35	0.39	0.37	0.35	0.36	0.34	0.33	0.35	0.33	0.32	0.34	0.33	0.32	0.31			
		4	0.38	0.35	0.32	0.37	0.34	0.32	0.33	0.31	0.30	0.32	0.31	0.29	0.32	0.30	0.29	0.28			
		5	0.36	0.32	0.29	0.35	0.32	0.29	0.31	0.29	0.27	0.30	0.28	0.27	0.30	0.28	0.27	0.26			
		6	0.34	0.30	0.27	0.33	0.29	0.27	0.29	0.27	0.25	0.28	0.26	0.25	0.28	0.26	0.25	0.24			
		7	0.32	0.28	0.25	0.31	0.27	0.25	0.27	0.25	0.23	0.26	0.24	0.23	0.26	0.24	0.23	0.22			
		8	0.30	0.26	0.23	0.29	0.25	0.23	0.25	0.23	0.21	0.25	0.23	0.21	0.24	0.22	0.21	0.20			
		9	0.28	0.24	0.21	0.28	0.24	0.21	0.23	0.21	0.20	0.23	0.21	0.19	0.23	0.21	0.19	0.19			
10	0.27	0.22	0.20	0.26	0.22	0.20	0.22	0.20	0.18	0.22	0.20	0.18	0.21	0.19	0.18	0.17					
 Metal halide downlight		Lamp = M100/C/U SC (along, across, 45°) = 1.2, 1.2, 1.1																			
		0	0.76	0.76	0.76	0.74	0.74	0.74	0.71	0.71	0.71	0.68	0.68	0.68	0.65	0.65	0.65	0.64			
		1	0.72	0.70	0.68	0.70	0.69	0.67	0.66	0.65	0.64	0.64	0.63	0.62	0.61	0.61	0.60	0.59			
		2	0.68	0.64	0.62	0.66	0.63	0.61	0.61	0.59	0.57	0.59	0.57	0.56	0.57	0.56	0.55	0.54			
		3	0.64	0.59	0.56	0.63	0.58	0.55	0.57	0.54	0.52	0.55	0.53	0.51	0.54	0.52	0.50	0.49			
		4	0.60	0.55	0.51	0.59	0.54	0.50	0.52	0.49	0.47	0.51	0.48	0.46	0.50	0.48	0.46	0.45			
		5	0.57	0.51	0.46	0.55	0.50	0.46	0.49	0.45	0.43	0.48	0.45	0.42	0.47	0.44	0.42	0.41			
		6	0.53	0.47	0.43	0.52	0.46	0.42	0.45	0.42	0.39	0.44	0.41	0.39	0.43	0.41	0.38	0.37			
		7	0.50	0.43	0.39	0.49	0.43	0.39	0.42	0.39	0.36	0.41	0.38	0.36	0.41	0.38	0.35	0.34			
		8	0.47	0.41	0.36	0.46	0.40	0.36	0.39	0.36	0.33	0.39	0.35	0.33	0.38	0.35	0.33	0.32			
		9	0.45	0.38	0.34	0.44	0.37	0.33	0.37	0.33	0.31	0.36	0.33	0.31	0.36	0.33	0.30	0.29			
10	0.42	0.35	0.31	0.42	0.35	0.31	0.35	0.31	0.28	0.34	0.31	0.28	0.34	0.30	0.28	0.27					

Figure 9-28 Continued

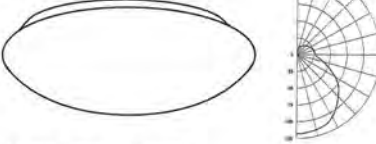
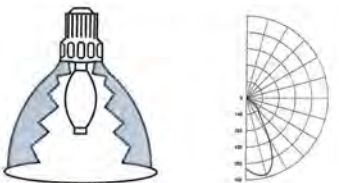
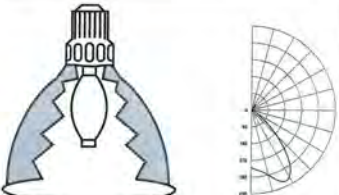
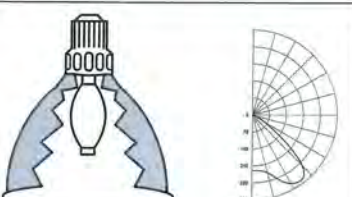
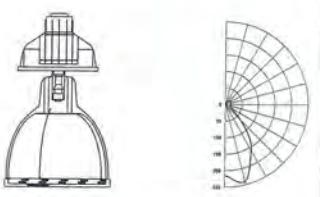
Typical Luminaire	Typical Intensity Distribution	pcc →																
		80			70			50			30			10			0	
		pw →			70			50			30			10			0	
		RCR ↓	Lamp = 22 & 32W circ.* SC (along, across, 45°) = 1.3, 1.3, 1.5															
			EFF = 55.9%	% DN = 76.2%			% UP = 23.8%											
11		0	0.63	0.63	0.63	0.60	0.60	0.60	0.55	0.55	0.55	0.50	0.50	0.50	0.45	0.45	0.45	0.43
		1	0.57	0.54	0.51	0.54	0.51	0.48	0.46	0.44	0.42	0.42	0.40	0.39	0.38	0.36	0.35	0.33
		2	0.51	0.46	0.42	0.48	0.44	0.40	0.40	0.37	0.34	0.36	0.33	0.31	0.32	0.30	0.29	0.27
		3	0.46	0.40	0.35	0.44	0.38	0.34	0.35	0.31	0.28	0.31	0.28	0.26	0.28	0.26	0.24	0.22
		4	0.42	0.35	0.30	0.40	0.34	0.29	0.31	0.27	0.24	0.28	0.24	0.22	0.25	0.22	0.20	0.19
		5	0.39	0.31	0.26	0.37	0.30	0.25	0.27	0.23	0.20	0.25	0.21	0.19	0.22	0.20	0.17	0.16
		6	0.36	0.28	0.23	0.34	0.27	0.22	0.24	0.20	0.18	0.22	0.19	0.16	0.20	0.17	0.15	0.14
		7	0.33	0.25	0.20	0.31	0.24	0.20	0.22	0.18	0.15	0.20	0.17	0.14	0.18	0.16	0.13	0.12
		8	0.31	0.23	0.18	0.29	0.22	0.18	0.20	0.16	0.14	0.18	0.15	0.13	0.17	0.14	0.12	0.11
		9	0.28	0.21	0.16	0.27	0.20	0.16	0.18	0.15	0.12	0.17	0.14	0.11	0.16	0.13	0.11	0.10
		10	0.27	0.19	0.15	0.25	0.19	0.14	0.17	0.13	0.11	0.16	0.13	0.10	0.14	0.12	0.10	0.09
CFL surface-mounted disk																		
12		Lamp = M400/C/U SC (along, across, 45°) = 1.1, 1.1, 1																
			EFF = 87.5%	% DN = 85.9%			% UP = 1.6%											
		0	1.04	1.04	1.04	1.01	1.01	1.01	0.96	0.96	0.96	0.92	0.92	0.92	0.88	0.88	0.88	0.86
		1	0.98	0.95	0.93	0.96	0.93	0.91	0.89	0.87	0.86	0.86	0.84	0.83	0.82	0.81	0.80	0.78
		2	0.92	0.87	0.83	0.90	0.85	0.82	0.82	0.79	0.76	0.79	0.77	0.74	0.77	0.75	0.73	0.71
		3	0.86	0.80	0.75	0.84	0.78	0.74	0.76	0.72	0.69	0.73	0.70	0.67	0.71	0.68	0.66	0.64
		4	0.81	0.73	0.68	0.79	0.72	0.67	0.70	0.66	0.62	0.68	0.64	0.61	0.66	0.63	0.60	0.59
		5	0.76	0.68	0.62	0.74	0.67	0.61	0.65	0.60	0.56	0.63	0.59	0.56	0.62	0.58	0.55	0.54
		6	0.72	0.63	0.57	0.70	0.62	0.56	0.60	0.55	0.52	0.59	0.54	0.51	0.57	0.54	0.51	0.49
		7	0.67	0.58	0.52	0.66	0.58	0.52	0.56	0.51	0.47	0.55	0.50	0.47	0.54	0.50	0.47	0.45
		8	0.64	0.54	0.48	0.62	0.54	0.48	0.53	0.47	0.44	0.51	0.47	0.43	0.50	0.46	0.43	0.42
		9	0.60	0.51	0.45	0.59	0.50	0.45	0.49	0.44	0.41	0.48	0.44	0.40	0.47	0.43	0.40	0.39
		10	0.57	0.48	0.42	0.56	0.47	0.42	0.46	0.41	0.38	0.45	0.41	0.38	0.45	0.40	0.37	0.36
High bay, open metal reflector, narrow																		
13		Lamp = M400/C/U SC (along, across, 45°) = 1.6, 1.6, 1.4																
			EFF = 83.9%	% DN = 95.2%			% UP = 4.8%											
		0	0.99	0.99	0.99	0.96	0.96	0.96	0.91	0.91	0.91	0.86	0.86	0.86	0.82	0.82	0.82	0.80
		1	0.93	0.90	0.87	0.90	0.88	0.85	0.83	0.81	0.80	0.80	0.78	0.77	0.76	0.75	0.74	0.72
		2	0.86	0.81	0.77	0.84	0.79	0.75	0.76	0.73	0.70	0.73	0.70	0.68	0.70	0.68	0.66	0.64
		3	0.80	0.73	0.68	0.78	0.72	0.67	0.65	0.65	0.61	0.66	0.63	0.60	0.64	0.61	0.58	0.57
		4	0.75	0.67	0.61	0.73	0.65	0.60	0.63	0.58	0.54	0.61	0.57	0.53	0.58	0.55	0.52	0.51
		5	0.70	0.61	0.54	0.68	0.59	0.54	0.57	0.52	0.48	0.55	0.51	0.48	0.54	0.50	0.47	0.45
		6	0.65	0.55	0.49	0.63	0.54	0.48	0.53	0.47	0.43	0.51	0.46	0.43	0.49	0.45	0.42	0.41
		7	0.60	0.51	0.44	0.59	0.50	0.44	0.48	0.43	0.39	0.47	0.42	0.39	0.45	0.41	0.38	0.37
		8	0.56	0.47	0.40	0.55	0.46	0.40	0.44	0.39	0.35	0.43	0.38	0.35	0.42	0.38	0.34	0.33
		9	0.53	0.43	0.37	0.52	0.42	0.36	0.41	0.36	0.32	0.40	0.35	0.32	0.39	0.35	0.31	0.30
		10	0.50	0.40	0.34	0.48	0.39	0.33	0.38	0.33	0.29	0.37	0.32	0.29	0.36	0.32	0.29	0.27
High bay, open metal reflector, medium																		
14		Lamp = M400/C/U SC (along, across, 45°) = 1.9, 1.9, 1.7																
			EFF = 83.8%	% DN = 97			% UP = 3											
		0	0.99	0.99	0.99	0.97	0.97	0.97	0.92	0.92	0.92	0.87	0.87	0.87	0.83	0.83	0.83	0.81
		1	0.92	0.89	0.86	0.90	0.87	0.84	0.83	0.81	0.79	0.80	0.78	0.76	0.76	0.75	0.74	0.72
		2	0.85	0.80	0.75	0.83	0.78	0.73	0.75	0.71	0.68	0.72	0.69	0.66	0.69	0.66	0.64	0.62
		3	0.79	0.71	0.65	0.76	0.70	0.64	0.67	0.62	0.58	0.64	0.60	0.57	0.62	0.59	0.56	0.54
		4	0.72	0.63	0.57	0.70	0.62	0.56	0.60	0.55	0.51	0.58	0.53	0.50	0.56	0.52	0.49	0.47
		5	0.67	0.57	0.50	0.65	0.56	0.50	0.54	0.48	0.44	0.52	0.47	0.43	0.50	0.46	0.43	0.41
		6	0.62	0.51	0.44	0.60	0.50	0.44	0.49	0.43	0.39	0.47	0.42	0.38	0.46	0.41	0.38	0.36
		7	0.57	0.46	0.40	0.56	0.46	0.39	0.44	0.38	0.34	0.43	0.38	0.34	0.42	0.37	0.33	0.32
		8	0.53	0.42	0.35	0.52	0.42	0.35	0.40	0.34	0.30	0.39	0.34	0.30	0.38	0.33	0.30	0.28
		9	0.49	0.39	0.32	0.48	0.38	0.32	0.37	0.31	0.27	0.36	0.31	0.27	0.35	0.30	0.27	0.25
		10	0.46	0.35	0.29	0.45	0.35	0.29	0.34	0.28	0.24	0.33	0.28	0.24	0.32	0.27	0.24	0.22
High bay, open metal reflector, wide																		
15		Lamp = M400/C/U SC (along, across, 45°) = 1.1, 1.1, 1.1																
			EFF = 61.4%	% DN = 80.6			% UP = 19.4											
		0	0.70	0.70	0.70	0.67	0.67	0.67	0.62	0.62	0.62	0.56	0.56	0.56	0.52	0.52	0.52	0.49
		1	0.65	0.62	0.60	0.62	0.59	0.57	0.55	0.53	0.52	0.50	0.49	0.48	0.46	0.45	0.44	0.42
		2	0.60	0.55	0.52	0.57	0.53	0.50	0.49	0.47	0.45	0.46	0.44	0.42	0.42	0.41	0.39	0.37
		3	0.56	0.50	0.46	0.53	0.48	0.44	0.45	0.42	0.39	0.42	0.39	0.37	0.39	0.37	0.35	0.33
		4	0.52	0.45	0.41	0.49	0.44	0.40	0.41	0.38	0.35	0.38	0.35	0.33	0.36	0.33	0.32	0.30
		5	0.48	0.41	0.37	0.46	0.40	0.36	0.38	0.34	0.31	0.35	0.32	0.30	0.33	0.31	0.29	0.27
		6	0.45	0.38	0.33	0.43	0.37	0.33	0.35	0.31	0.28	0.33	0.30	0.27	0.31	0.28	0.26	0.25
		7	0.42	0.35	0.30	0.40	0.34	0.30	0.32	0.28	0.26	0.30	0.27	0.25	0.29	0.26	0.24	0.23
		8	0.40	0.32	0.28	0.38	0.31	0.27	0.30	0.26	0.24	0.28	0.25	0.23	0.27	0.24	0.22	0.21
		9	0.37	0.30	0.26	0.36	0.29	0.25	0.28	0.24	0.22	0.26	0.23	0.21	0.25	0.22	0.20	0.19
		10	0.35	0.28	0.24	0.34	0.27	0.23	0.26	0.22	0.20	0.25	0.22	0.19	0.23	0.21	0.19	0.18
High bay, open prismatic reflector, narrow																		

Figure 9-28 Continued

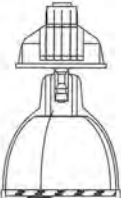
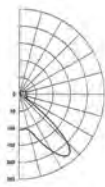
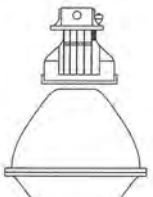
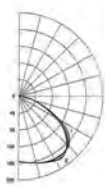
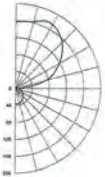
Typical Luminaire	Typical Intensity Distribution	$\rho_{CC} \rightarrow$			80			70			50			30			10			0
		$\rho_W \rightarrow$			70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR $\downarrow$			EFF = 59%			% DN = 77.9%			% UP = 22.1%			Lamp = M400/C/U SC (along, across, 45°) = 1.3, 1.3, 1.2						
16 		0	0.67	0.67	0.67	0.64	0.64	0.64	0.58	0.58	0.58	0.53	0.53	0.53	0.48	0.48	0.48	0.48	0.48	0.48
		1	0.62	0.59	0.57	0.59	0.57	0.55	0.52	0.50	0.49	0.48	0.46	0.45	0.43	0.43	0.42	0.42	0.42	0.40
		2	0.57	0.53	0.50	0.55	0.51	0.48	0.47	0.45	0.43	0.43	0.41	0.40	0.40	0.38	0.37	0.35	0.31	0.35
		3	0.53	0.48	0.44	0.51	0.46	0.43	0.43	0.40	0.37	0.40	0.37	0.35	0.36	0.35	0.33	0.31	0.28	0.31
		4	0.50	0.44	0.39	0.47	0.42	0.38	0.39	0.36	0.33	0.36	0.34	0.32	0.34	0.32	0.30	0.28	0.26	0.28
		5	0.46	0.40	0.35	0.44	0.38	0.34	0.36	0.33	0.30	0.33	0.31	0.28	0.31	0.29	0.27	0.25	0.23	0.26
		6	0.43	0.37	0.32	0.41	0.35	0.31	0.33	0.30	0.27	0.31	0.28	0.26	0.29	0.27	0.25	0.23	0.21	0.23
		7	0.40	0.34	0.29	0.39	0.33	0.28	0.31	0.27	0.25	0.29	0.26	0.24	0.27	0.24	0.23	0.21	0.20	0.21
		8	0.38	0.31	0.27	0.36	0.30	0.26	0.28	0.25	0.22	0.27	0.24	0.22	0.25	0.23	0.21	0.20	0.18	0.20
		9	0.36	0.29	0.24	0.34	0.28	0.24	0.26	0.23	0.21	0.25	0.22	0.20	0.23	0.21	0.19	0.18	0.16	0.18
		10	0.33	0.27	0.23	0.32	0.26	0.22	0.24	0.21	0.19	0.23	0.20	0.18	0.22	0.19	0.18	0.17	0.15	0.17
17 		EFF = 61.5%			% DN = 83.7%			% UP = 16.3%			Lamp = M400/C/U SC (along, across, 45°) = 2.2, 2.2, 1.8									
		0	0.71	0.71	0.71	0.68	0.68	0.68	0.63	0.63	0.63	0.58	0.58	0.58	0.54	0.54	0.54	0.51	0.49	0.51
		1	0.65	0.62	0.59	0.62	0.59	0.57	0.55	0.53	0.52	0.51	0.50	0.48	0.47	0.46	0.45	0.43	0.42	0.43
		2	0.59	0.55	0.51	0.57	0.53	0.49	0.49	0.46	0.43	0.45	0.43	0.41	0.42	0.40	0.39	0.37	0.35	0.37
		3	0.54	0.48	0.44	0.52	0.47	0.42	0.43	0.40	0.37	0.40	0.38	0.35	0.38	0.35	0.33	0.32	0.30	0.32
		4	0.50	0.43	0.38	0.48	0.42	0.37	0.39	0.35	0.32	0.36	0.33	0.30	0.34	0.31	0.29	0.27	0.25	0.27
		5	0.46	0.38	0.33	0.44	0.37	0.32	0.35	0.31	0.27	0.32	0.29	0.26	0.30	0.27	0.25	0.24	0.22	0.24
		6	0.42	0.34	0.29	0.40	0.33	0.28	0.31	0.27	0.24	0.29	0.26	0.23	0.27	0.24	0.22	0.21	0.19	0.21
		7	0.39	0.31	0.26	0.37	0.30	0.25	0.28	0.24	0.21	0.27	0.23	0.20	0.25	0.22	0.19	0.18	0.16	0.18
		8	0.36	0.28	0.23	0.35	0.27	0.22	0.26	0.21	0.18	0.24	0.20	0.18	0.23	0.19	0.17	0.16	0.14	0.16
		9	0.34	0.25	0.21	0.32	0.25	0.20	0.23	0.19	0.16	0.22	0.18	0.16	0.21	0.18	0.15	0.14	0.12	0.14
		10	0.31	0.23	0.19	0.30	0.23	0.18	0.21	0.17	0.15	0.20	0.17	0.14	0.19	0.16	0.14	0.12	0.10	0.12
18 		EFF = 72.5%			% DN = 97.8%			% UP = 2.2%			Lamp = M400/C/U SC (along, across, 45°) = 1.7, 1.7, 1.7									
		0	0.86	0.86	0.86	0.84	0.84	0.84	0.80	0.80	0.80	0.76	0.76	0.76	0.73	0.73	0.73	0.71	0.69	0.71
		1	0.78	0.75	0.71	0.76	0.73	0.70	0.69	0.67	0.65	0.66	0.64	0.63	0.63	0.62	0.60	0.59	0.57	0.59
		2	0.71	0.65	0.60	0.69	0.63	0.59	0.60	0.56	0.53	0.58	0.54	0.52	0.55	0.53	0.50	0.49	0.47	0.49
		3	0.64	0.56	0.50	0.62	0.55	0.50	0.53	0.48	0.44	0.51	0.46	0.43	0.48	0.45	0.42	0.40	0.38	0.40
		4	0.59	0.50	0.43	0.57	0.49	0.42	0.47	0.41	0.37	0.45	0.40	0.36	0.43	0.39	0.36	0.34	0.32	0.34
		5	0.54	0.44	0.37	0.52	0.43	0.37	0.41	0.36	0.32	0.40	0.35	0.31	0.38	0.34	0.31	0.29	0.27	0.29
		6	0.49	0.39	0.33	0.48	0.39	0.32	0.37	0.31	0.27	0.36	0.31	0.27	0.34	0.30	0.26	0.25	0.23	0.25
		7	0.46	0.35	0.29	0.44	0.35	0.28	0.33	0.28	0.24	0.32	0.27	0.23	0.31	0.27	0.23	0.22	0.20	0.22
		8	0.42	0.32	0.26	0.41	0.31	0.25	0.30	0.25	0.21	0.29	0.24	0.21	0.28	0.24	0.21	0.19	0.17	0.19
		9	0.39	0.29	0.23	0.38	0.29	0.23	0.28	0.22	0.19	0.27	0.22	0.18	0.26	0.22	0.18	0.17	0.15	0.17
		10	0.37	0.27	0.21	0.36	0.26	0.21	0.26	0.20	0.17	0.25	0.20	0.17	0.24	0.20	0.16	0.15	0.13	0.15
19 		EFF = 75.3%			% DN = 8.1			% UP = 91.9			Lamp = M175/C* SC (along, across, 45°) = 1.3, 1.3, 1.5									
		0	0.73	0.73	0.73	0.63	0.63	0.63	0.45	0.45	0.45	0.29	0.29	0.29	0.13	0.13	0.13	0.06	0.05	0.06
		1	0.66	0.63	0.60	0.57	0.55	0.52	0.39	0.38	0.36	0.25	0.24	0.23	0.11	0.11	0.11	0.05	0.04	0.05
		2	0.60	0.55	0.51	0.52	0.48	0.44	0.34	0.32	0.30	0.21	0.20	0.19	0.10	0.09	0.09	0.04	0.03	0.04
		3	0.55	0.48	0.43	0.47	0.42	0.37	0.30	0.27	0.25	0.19	0.17	0.16	0.09	0.08	0.07	0.03	0.02	0.03
		4	0.50	0.42	0.37	0.43	0.37	0.32	0.26	0.23	0.21	0.17	0.15	0.13	0.08	0.07	0.06	0.02	0.01	0.02
		5	0.46	0.37	0.32	0.39	0.33	0.28	0.23	0.20	0.18	0.15	0.13	0.11	0.07	0.06	0.05	0.02	0.01	0.02
		6	0.42	0.33	0.28	0.36	0.29	0.24	0.21	0.18	0.15	0.13	0.11	0.10	0.06	0.05	0.05	0.02	0.01	0.02
		7	0.39	0.30	0.24	0.33	0.26	0.21	0.19	0.16	0.13	0.12	0.10	0.09	0.05	0.05	0.04	0.02	0.01	0.02
		8	0.36	0.27	0.21	0.31	0.23	0.19	0.17	0.14	0.12	0.11	0.09	0.07	0.05	0.04	0.03	0.01	0.01	0.02
		9	0.33	0.24	0.19	0.28	0.21	0.17	0.15	0.12	0.10	0.10	0.08	0.07	0.05	0.04	0.03	0.01	0.01	0.02
		10	0.31	0.22	0.17	0.26	0.19	0.15	0.14	0.11	0.09	0.09	0.07	0.06	0.04	0.03	0.03	0.01	0.01	0.02
20 		EFF = 81.5%			% DN = 15.3			% UP = 84.7			Lamp = (4) FT39* SC (along, across, 45°) = 1.3, 1.3, 1.5									
		0	0.81	0.81	0.81	0.71	0.71	0.71	0.52	0.52	0.52	0.35	0.35	0.35	0.20	0.20	0.20	0.13	0.10	0.13
		1	0.73	0.69	0.66	0.64	0.61	0.58	0.45	0.43	0.42	0.30	0.29	0.28	0.17	0.16	0.16	0.10	0.08	0.10
		2	0.66	0.60	0.55	0.58	0.53	0.49	0.39	0.36	0.34	0.26	0.25	0.23	0.15	0.14	0.13	0.08	0.06	0.08
		3	0.60	0.53	0.47	0.53	0.46	0.42	0.34	0.31	0.29	0.23	0.21	0.20	0.13	0.12	0.11	0.06	0.05	0.06
		4	0.55	0.47	0.40	0.48	0.41	0.36	0.30	0.27	0.24	0.20	0.18	0.17	0.11	0.10	0.09	0.05	0.04	0.05
		5	0.50	0.41	0.35	0.44	0.36	0.31	0.27	0.23	0.20	0.18	0.16	0.14	0.10	0.09	0.08	0.05	0.04	0.05
		6	0.46	0.37	0.30	0.40	0.32	0.27	0.24	0.20	0.18	0.16	0.14	0.12	0.09	0.08	0.07	0.04	0.03	0.04
		7	0.42	0.33	0.27	0.37	0.29	0.24	0.22	0.18	0.15	0.15	0.12	0.11	0.08	0.07	0.06	0.04	0.03	0.04
		8	0.39	0.30	0.24	0.34	0.26	0.21	0.20	0.16	0.13	0.13	0.11	0.09	0.08	0.06	0.05	0.03	0.02	0.03

Figure 9-28 Continued

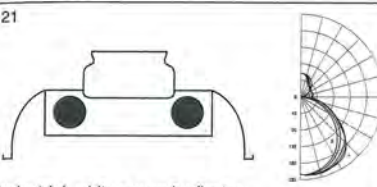
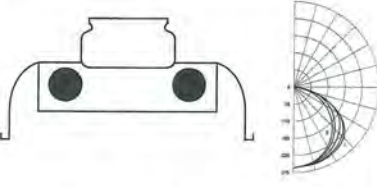
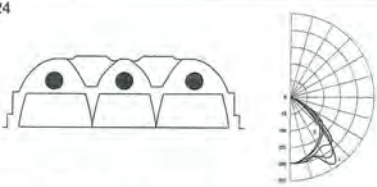
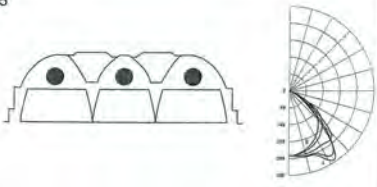
Typical Luminaire	Typical Intensity Distribution	$\rho_{cc} \rightarrow$			80			70			50			30			10			0		
		$\rho_w \rightarrow$			70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0	0	
		RCR $\downarrow$			Lamp = (2) F40T12 SC (along, across, 45°) = 1.3, 1.5, 1.5																	
21		0	1.03	1.03	1.03	0.98	0.98	0.98	0.90	0.90	0.90	0.82	0.82	0.82	0.74	0.74	0.74	0.71	0.71	0.71	0.71	
		1	0.93	0.89	0.85	0.89	0.85	0.81	0.77	0.74	0.72	0.70	0.68	0.66	0.64	0.62	0.61	0.58	0.58	0.58	0.58	
		2	0.84	0.77	0.71	0.80	0.74	0.68	0.67	0.63	0.59	0.61	0.58	0.54	0.56	0.53	0.50	0.47	0.47	0.47	0.47	
		3	0.77	0.67	0.60	0.73	0.64	0.58	0.59	0.53	0.49	0.54	0.49	0.45	0.49	0.45	0.42	0.40	0.40	0.40	0.40	
		4	0.70	0.59	0.51	0.66	0.57	0.50	0.52	0.46	0.41	0.48	0.43	0.39	0.44	0.39	0.36	0.33	0.33	0.33	0.33	
		5	0.64	0.53	0.45	0.61	0.51	0.43	0.46	0.40	0.35	0.43	0.37	0.33	0.39	0.35	0.31	0.29	0.29	0.29	0.29	
		6	0.59	0.47	0.39	0.56	0.45	0.38	0.42	0.35	0.31	0.38	0.33	0.29	0.35	0.31	0.27	0.25	0.25	0.25	0.25	
		7	0.55	0.43	0.35	0.52	0.41	0.34	0.38	0.32	0.27	0.35	0.30	0.26	0.32	0.28	0.24	0.22	0.22	0.22	0.22	
		8	0.51	0.39	0.31	0.48	0.37	0.30	0.34	0.28	0.24	0.32	0.27	0.23	0.29	0.25	0.21	0.19	0.19	0.19	0.19	
		9	0.47	0.35	0.28	0.45	0.34	0.27	0.32	0.26	0.21	0.29	0.24	0.20	0.27	0.23	0.19	0.17	0.17	0.17	0.17	
		10	0.44	0.33	0.26	0.42	0.31	0.25	0.29	0.23	0.19	0.27	0.22	0.18	0.25	0.21	0.17	0.16	0.16	0.16	0.16	
22		EFF = 86.9%			% DN = 100%			% UP = 0%			Lamp = (2) F40T12 SC (along, across, 45°) = 1.3, 1.5, 1.5											
		0	1.03	1.03	1.03	1.01	1.01	1.01	0.97	0.97	0.97	0.92	0.92	0.92	0.89	0.89	0.89	0.87	0.87	0.87	0.87	
		1	0.94	0.90	0.86	0.92	0.88	0.84	0.84	0.81	0.79	0.81	0.79	0.76	0.78	0.76	0.74	0.72	0.72	0.72	0.72	
		2	0.85	0.78	0.72	0.83	0.76	0.70	0.73	0.68	0.64	0.70	0.66	0.63	0.67	0.64	0.61	0.59	0.59	0.59	0.59	
		3	0.77	0.68	0.60	0.75	0.66	0.59	0.64	0.58	0.53	0.61	0.56	0.52	0.59	0.55	0.51	0.49	0.49	0.49	0.49	
		4	0.70	0.60	0.52	0.68	0.58	0.51	0.56	0.50	0.45	0.54	0.48	0.44	0.52	0.47	0.43	0.41	0.41	0.41	0.41	
		5	0.65	0.53	0.45	0.63	0.52	0.44	0.50	0.43	0.38	0.48	0.42	0.38	0.47	0.41	0.37	0.35	0.35	0.35	0.35	
		6	0.59	0.47	0.39	0.58	0.47	0.39	0.45	0.38	0.33	0.43	0.37	0.33	0.42	0.37	0.32	0.31	0.31	0.31	0.31	
		7	0.55	0.43	0.35	0.53	0.42	0.35	0.41	0.34	0.29	0.39	0.33	0.29	0.38	0.33	0.29	0.27	0.27	0.27	0.27	
		8	0.51	0.39	0.31	0.50	0.38	0.31	0.37	0.30	0.26	0.36	0.30	0.26	0.35	0.29	0.25	0.24	0.24	0.24	0.24	
		9	0.48	0.36	0.28	0.46	0.35	0.28	0.34	0.28	0.23	0.33	0.27	0.23	0.32	0.27	0.23	0.21	0.21	0.21	0.21	
		10	0.45	0.33	0.26	0.43	0.32	0.25	0.31	0.25	0.21	0.31	0.25	0.21	0.30	0.24	0.21	0.19	0.19	0.19	0.19	
23		EFF = 89.3%			% DN = 86.4%			% UP = 13.6%			Lamp = (2) F40T12 SC (along, across, 45°) = 1.3, 1.5, 1.6											
		0	1.03	1.03	1.03	1.00	1.00	1.00	0.92	0.92	0.92	0.86	0.86	0.86	0.80	0.80	0.80	0.77	0.77	0.77	0.77	
		1	0.93	0.88	0.83	0.89	0.84	0.80	0.78	0.75	0.72	0.73	0.70	0.68	0.67	0.65	0.63	0.61	0.61	0.61	0.61	
		2	0.83	0.75	0.68	0.80	0.72	0.66	0.67	0.62	0.58	0.62	0.58	0.55	0.58	0.55	0.52	0.49	0.49	0.49	0.49	
		3	0.75	0.65	0.57	0.72	0.63	0.56	0.58	0.52	0.47	0.54	0.49	0.45	0.50	0.46	0.43	0.40	0.40	0.40	0.40	
		4	0.69	0.57	0.49	0.65	0.55	0.47	0.51	0.45	0.40	0.48	0.42	0.38	0.44	0.40	0.36	0.34	0.34	0.34	0.34	
		5	0.63	0.51	0.42	0.60	0.49	0.41	0.46	0.39	0.34	0.43	0.37	0.32	0.40	0.35	0.31	0.29	0.29	0.29	0.29	
		6	0.58	0.45	0.37	0.55	0.44	0.36	0.41	0.34	0.29	0.38	0.32	0.28	0.36	0.31	0.27	0.25	0.25	0.25	0.25	
		7	0.53	0.41	0.33	0.51	0.40	0.32	0.37	0.30	0.26	0.35	0.29	0.25	0.33	0.27	0.24	0.22	0.22	0.22	0.22	
		8	0.50	0.37	0.29	0.47	0.36	0.29	0.34	0.27	0.23	0.32	0.26	0.22	0.30	0.25	0.21	0.19	0.19	0.19	0.19	
		9	0.46	0.34	0.26	0.44	0.33	0.26	0.31	0.25	0.20	0.29	0.24	0.19	0.27	0.22	0.19	0.17	0.17	0.17	0.17	
		10	0.43	0.31	0.24	0.41	0.30	0.23	0.29	0.22	0.18	0.27	0.21	0.18	0.25	0.20	0.17	0.15	0.15	0.15	0.15	
24		EFF = 72.7%			% DN = 100			% UP = 0			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.6, 1.6											
		0	0.87	0.87	0.87	0.85	0.85	0.85	0.81	0.81	0.81	0.77	0.77	0.77	0.74	0.74	0.74	0.73	0.73	0.73	0.73	
		1	0.81	0.78	0.76	0.79	0.77	0.74	0.74	0.72	0.70	0.71	0.69	0.68	0.68	0.67	0.66	0.65	0.65	0.65	0.65	
		2	0.75	0.70	0.66	0.73	0.69	0.65	0.66	0.63	0.61	0.64	0.61	0.59	0.62	0.60	0.58	0.57	0.57	0.57	0.57	
		3	0.69	0.63	0.58	0.68	0.62	0.57	0.60	0.56	0.52	0.58	0.54	0.52	0.56	0.53	0.51	0.49	0.49	0.49	0.49	
		4	0.64	0.56	0.51	0.62	0.55	0.50	0.54	0.49	0.46	0.52	0.48	0.45	0.51	0.47	0.44	0.43	0.43	0.43	0.43	
		5	0.59	0.51	0.45	0.58	0.50	0.44	0.48	0.44	0.40	0.47	0.43	0.40	0.46	0.42	0.39	0.38	0.38	0.38	0.38	
		6	0.55	0.46	0.40	0.53	0.45	0.40	0.44	0.39	0.35	0.43	0.38	0.35	0.42	0.38	0.35	0.33	0.33	0.33	0.33	
		7	0.51	0.42	0.36	0.50	0.41	0.36	0.40	0.35	0.31	0.39	0.35	0.31	0.38	0.34	0.31	0.30	0.30	0.30	0.30	
		8	0.47	0.38	0.32	0.46	0.38	0.32	0.37	0.32	0.28	0.36	0.31	0.28	0.35	0.31	0.28	0.27	0.27	0.27	0.27	
		9	0.44	0.35	0.29	0.43	0.35	0.29	0.34	0.29	0.25	0.33	0.29	0.25	0.32	0.28	0.25	0.24	0.24	0.24	0.24	
		10	0.41	0.32	0.27	0.40	0.32	0.27	0.31	0.26	0.23	0.31	0.26	0.23	0.30	0.26	0.23	0.22	0.22	0.22	0.22	
25		EFF = 66.2%			% DN = 100			% UP = 0			Lamp = (3) F40T12 SC (along, across, 45°) = 1.3, 1.6, 1.5											
		0	0.79	0.79	0.79	0.77	0.77	0.77	0.74	0.74	0.74	0.70	0.70	0.70	0.68	0.68	0.68	0.66	0.66	0.66	0.66	
		1	0.74	0.72	0.69	0.72	0.70	0.68	0.67	0.66	0.64	0.65	0.64	0.62	0.62	0.61	0.61	0.59	0.59	0.59	0.59	
		2	0.69	0.64	0.61	0.67	0.63	0.60	0.61	0.58	0.56	0.59	0.57	0.55	0.57	0.55	0.53	0.52	0.52	0.52	0.52	
		3	0.63	0.58	0.53	0.62	0.57	0.53	0.55	0.51	0.48	0.53	0.50	0.48	0.52	0.49	0.47	0.46	0.46	0.46	0.46	
		4	0.59	0.52	0.47	0.57	0.51	0.47	0.50	0.46	0.42	0.48	0.45	0.42	0.47	0.44	0.41	0.40	0.40	0.40	0.40	
		5	0.54	0.47	0.42	0.53	0.46	0.41	0.45	0.41	0.37	0.44	0.40	0.37	0.43	0.39	0.37	0.35	0.35	0.35	0.35	
		6	0.50	0.43	0.37	0.49	0.42	0.37	0.41	0.36	0.33	0.40	0.36	0.33	0.39	0.35	0.33	0.31	0.31	0.31	0.31	
		7	0.47	0.39	0.33	0.46	0.38	0.33	0.37	0.33	0.30	0.36	0.32	0.29	0.35	0.32	0.29	0.28	0.28	0.28	0.28	
		8	0.44	0.35	0.30	0.43	0.35	0.30	0.34	0.30	0.26	0.33	0.29	0.26	0.33	0.29	0.26	0.25	0.25	0.25	0.25	
		9	0.41	0.33	0.27	0.40	0.32	0.27	0.31	0.27	0.24	0.31	0.27	0.24	0.30	0.26	0.24	0.23	0.23	0.23	0.23	
		10	0.38	0.30	0.25	0.37	0.30	0.25	0.29	0.25	0.22	0.28	0.24	0.22	0.28	0.24	0.22	0.20	0.20	0.20	0.20	

Figure 9-28 Continued

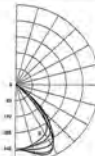
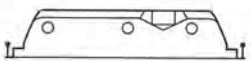
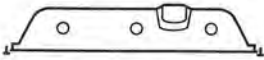
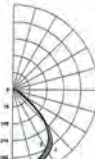
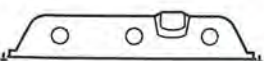
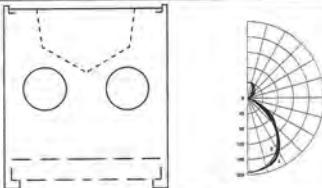
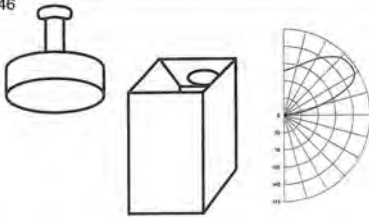
Typical Luminaire		Typical Intensity Distribution	Typical Intensity Distribution																		
			$\rho_{CC} \rightarrow$			80			70			50			30			10			0
			$\rho_W \rightarrow$			70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR $\downarrow$	EFF = 64.6%			% DN = 100%			% UP = 0%			Lamp = (3) F31T8/U/6 SC (along, across, 45°) = 1.3, 1.5, 1.3									
31			0	0.77	0.77	0.77	0.75	0.75	0.75	0.67	0.72	0.72	0.69	0.69	0.69	0.66	0.66	0.66	0.65		
			1	0.73	0.71	0.69	0.71	0.69	0.68	0.67	0.65	0.64	0.64	0.63	0.62	0.62	0.61	0.60	0.59		
			2	0.68	0.65	0.62	0.67	0.64	0.61	0.61	0.59	0.57	0.59	0.58	0.56	0.58	0.56	0.55	0.54		
			3	0.64	0.59	0.55	0.63	0.58	0.55	0.56	0.54	0.51	0.55	0.52	0.50	0.53	0.51	0.50	0.48		
			4	0.60	0.54	0.50	0.59	0.53	0.50	0.52	0.49	0.46	0.51	0.48	0.45	0.49	0.47	0.45	0.44		
			5	0.56	0.50	0.45	0.55	0.49	0.45	0.48	0.44	0.41	0.47	0.43	0.41	0.46	0.43	0.41	0.39		
			6	0.53	0.46	0.41	0.51	0.45	0.41	0.44	0.40	0.37	0.43	0.40	0.37	0.42	0.39	0.37	0.36		
			7	0.49	0.42	0.38	0.48	0.42	0.37	0.41	0.37	0.34	0.40	0.36	0.34	0.39	0.36	0.34	0.33		
			8	0.46	0.39	0.34	0.45	0.39	0.34	0.38	0.34	0.31	0.37	0.33	0.31	0.36	0.33	0.31	0.30		
			9	0.43	0.36	0.32	0.43	0.36	0.31	0.35	0.31	0.28	0.34	0.31	0.28	0.34	0.31	0.28	0.27		
			10	0.41	0.33	0.29	0.40	0.33	0.29	0.33	0.29	0.26	0.32	0.28	0.26	0.32	0.28	0.26	0.25		
32			EFF = 75.6%			% DN = 100%			% UP = 0%			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.3, 1.4									
			0	0.90	0.90	0.90	0.88	0.88	0.88	0.84	0.84	0.84	0.80	0.80	0.80	0.77	0.77	0.77	0.76		
			1	0.83	0.79	0.76	0.81	0.78	0.75	0.75	0.72	0.70	0.72	0.70	0.68	0.69	0.67	0.66	0.65		
			2	0.76	0.70	0.65	0.74	0.69	0.64	0.66	0.62	0.59	0.64	0.61	0.58	0.61	0.59	0.57	0.55		
			3	0.70	0.62	0.57	0.68	0.61	0.56	0.59	0.54	0.51	0.57	0.53	0.50	0.55	0.52	0.49	0.47		
			4	0.64	0.56	0.49	0.63	0.55	0.49	0.53	0.48	0.44	0.51	0.47	0.43	0.49	0.46	0.43	0.41		
			5	0.59	0.50	0.44	0.58	0.49	0.43	0.48	0.42	0.38	0.46	0.41	0.38	0.45	0.41	0.37	0.36		
			6	0.55	0.45	0.39	0.53	0.45	0.38	0.43	0.38	0.34	0.42	0.37	0.33	0.41	0.37	0.33	0.32		
			7	0.51	0.41	0.35	0.50	0.41	0.35	0.39	0.34	0.30	0.38	0.33	0.30	0.37	0.33	0.30	0.28		
			8	0.48	0.38	0.31	0.46	0.37	0.31	0.36	0.31	0.27	0.35	0.30	0.27	0.34	0.30	0.27	0.25		
			9	0.44	0.35	0.29	0.43	0.34	0.28	0.33	0.28	0.24	0.33	0.28	0.24	0.32	0.27	0.24	0.23		
			10	0.42	0.32	0.26	0.41	0.32	0.26	0.31	0.26	0.22	0.30	0.25	0.22	0.29	0.25	0.22	0.21		
33			EFF = 72.4%			% DN = 100%			% UP = 0%			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.3, 1.3									
			0	0.86	0.86	0.86	0.84	0.84	0.84	0.80	0.80	0.80	0.77	0.77	0.77	0.74	0.74	0.74	0.72		
			1	0.80	0.77	0.75	0.78	0.76	0.73	0.73	0.71	0.69	0.70	0.68	0.67	0.67	0.66	0.65	0.63		
			2	0.74	0.69	0.65	0.72	0.68	0.64	0.65	0.62	0.59	0.63	0.60	0.58	0.61	0.59	0.57	0.55		
			3	0.69	0.62	0.57	0.67	0.61	0.56	0.59	0.55	0.52	0.57	0.54	0.51	0.55	0.52	0.50	0.48		
			4	0.64	0.56	0.50	0.62	0.55	0.50	0.53	0.49	0.45	0.52	0.48	0.45	0.50	0.47	0.44	0.43		
			5	0.59	0.51	0.45	0.58	0.50	0.45	0.48	0.44	0.40	0.47	0.43	0.40	0.46	0.42	0.39	0.38		
			6	0.55	0.46	0.40	0.54	0.45	0.40	0.44	0.39	0.36	0.43	0.39	0.35	0.42	0.38	0.35	0.34		
			7	0.51	0.42	0.36	0.50	0.42	0.36	0.41	0.36	0.32	0.40	0.35	0.32	0.39	0.35	0.32	0.30		
			8	0.48	0.39	0.33	0.47	0.38	0.33	0.37	0.32	0.29	0.36	0.32	0.29	0.36	0.32	0.29	0.27		
			9	0.45	0.36	0.30	0.44	0.35	0.30	0.35	0.30	0.26	0.34	0.29	0.26	0.33	0.29	0.26	0.25		
			10	0.42	0.33	0.28	0.41	0.33	0.28	0.32	0.27	0.24	0.31	0.27	0.24	0.31	0.27	0.24	0.23		
34			EFF = 68.4%			% DN = 100			% UP = 0			Lamp = (3) FT40 SC (along, across, 45°) = 1.2, 1.3, 1.3									
			0	0.81	0.81	0.81	0.80	0.80	0.80	0.76	0.76	0.76	0.73	0.73	0.73	0.70	0.70	0.70	0.68		
			1	0.75	0.72	0.70	0.73	0.71	0.69	0.68	0.66	0.64	0.65	0.64	0.62	0.63	0.62	0.60	0.59		
			2	0.69	0.64	0.60	0.68	0.63	0.59	0.61	0.58	0.55	0.59	0.56	0.54	0.56	0.54	0.52	0.51		
			3	0.64	0.57	0.52	0.62	0.56	0.52	0.54	0.50	0.47	0.53	0.49	0.46	0.51	0.48	0.46	0.44		
			4	0.59	0.52	0.46	0.58	0.51	0.46	0.49	0.45	0.41	0.47	0.44	0.41	0.46	0.43	0.40	0.39		
			5	0.55	0.47	0.41	0.53	0.46	0.41	0.44	0.40	0.36	0.43	0.39	0.36	0.42	0.38	0.35	0.34		
			6	0.51	0.42	0.37	0.49	0.42	0.36	0.40	0.36	0.32	0.39	0.35	0.32	0.38	0.35	0.32	0.30		
			7	0.47	0.39	0.33	0.46	0.38	0.33	0.37	0.32	0.29	0.36	0.32	0.29	0.35	0.31	0.28	0.27		
			8	0.44	0.35	0.30	0.43	0.35	0.30	0.34	0.29	0.26	0.33	0.29	0.26	0.32	0.29	0.26	0.24		
			9	0.41	0.33	0.27	0.40	0.32	0.27	0.31	0.27	0.24	0.31	0.27	0.23	0.30	0.26	0.23	0.22		
			10	0.39	0.30	0.25	0.38	0.30	0.25	0.29	0.25	0.22	0.29	0.24	0.21	0.28	0.24	0.21	0.20		
35			EFF = 57.1%			% DN = 100			% UP = 0			Lamp = (2) F31T8/U/6 SC (along, across, 45°) = 1.2, 1.3, 1.4									
			0	0.68	0.68	0.68	0.66	0.66	0.66	0.63	0.63	0.63	0.61	0.61	0.61	0.58	0.58	0.58	0.57		
			1	0.64	0.62	0.60	0.62	0.60	0.59	0.58	0.57	0.55	0.56	0.55	0.54	0.54	0.53	0.52	0.51		
			2	0.59	0.55	0.52	0.58	0.54	0.51	0.52	0.50	0.48	0.51	0.49	0.47	0.49	0.47	0.46	0.45		
			3	0.55	0.50	0.46	0.53	0.49	0.45	0.47	0.44	0.42	0.46	0.43	0.41	0.44	0.42	0.40	0.39		
			4	0.51	0.45	0.40	0.49	0.44	0.40	0.43	0.39	0.36	0.41	0.38	0.36	0.40	0.38	0.36	0.34		
			5	0.47	0.40	0.36	0.46	0.40	0.36	0.39	0.35	0.32	0.38	0.34	0.32	0.37	0.34	0.31	0.30		
			6	0.43	0.37	0.32	0.42	0.36	0.32	0.35	0.31	0.28	0.34	0.31	0.28	0.33	0.30	0.28	0.27		
			7	0.40	0.33	0.29	0.39	0.33	0.29	0.32	0.28	0.25	0.31	0.28	0.25	0.31	0.27	0.25	0.24		
			8	0.38	0.31	0.26	0.37	0.30	0.26	0.29	0.26	0.23	0.29	0.25	0.23	0.28	0.25	0.23	0.22		
			9	0.35	0.28	0.24	0.34	0.28	0.24	0.27	0.23	0.21	0.27	0.23	0.21	0.26	0.23	0.21	0.20		
			10	0.33	0.26	0.22	0.32	0.26	0.22	0.25	0.21	0.19	0.25	0.21	0.19	0.24	0.21	0.19	0.18		

Figure 9-28 Continued

Typical Luminaire	Typical Intensity Distribution	$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$																																	
		80			70			50			30			10			0			80			70			50			30			10			0																					
		$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$			$\rho_{cc} \rightarrow$			$\rho_w \rightarrow$																								
41		RCR	EFF = 82.4%									% DN = 5.4%									% UP = 94.6%									Lamp = (2) F32T8 SC (along, across, 45°) = N/A																										
		↓	0.80 0.80 0.80									0.69 0.69 0.69									0.48 0.48 0.48									0.30 0.30 0.30									0.12 0.12 0.12									0.04 0.04 0.04								
		0	0.80	0.80	0.80	0.69	0.69	0.69	0.48	0.48	0.48	0.30	0.30	0.30	0.12	0.12	0.12	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04																			
		1	0.72	0.69	0.66	0.62	0.59	0.57	0.42	0.40	0.39	0.27	0.25	0.24	0.11	0.10	0.10	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04																			
		2	0.66	0.60	0.55	0.56	0.52	0.48	0.37	0.34	0.32	0.22	0.21	0.20	0.09	0.09	0.09	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03																			
		3	0.60	0.53	0.47	0.51	0.45	0.41	0.32	0.29	0.27	0.20	0.18	0.17	0.08	0.08	0.07	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02																			
		4	0.55	0.46	0.40	0.47	0.40	0.35	0.28	0.25	0.23	0.17	0.16	0.14	0.07	0.07	0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02																			
		5	0.50	0.41	0.35	0.43	0.36	0.30	0.25	0.22	0.19	0.16	0.14	0.12	0.07	0.06	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02																			
		6	0.46	0.37	0.30	0.39	0.32	0.27	0.23	0.19	0.17	0.14	0.12	0.11	0.06	0.05	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02																			
		7	0.42	0.33	0.27	0.36	0.28	0.23	0.20	0.17	0.14	0.13	0.11	0.09	0.05	0.05	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01																			
		8	0.39	0.29	0.24	0.33	0.26	0.21	0.18	0.15	0.13	0.11	0.09	0.08	0.05	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01																			
9	0.36	0.27	0.21	0.31	0.23	0.18	0.17	0.13	0.11	0.10	0.08	0.07	0.04	0.04	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01																					
10	0.33	0.24	0.19	0.29	0.21	0.16	0.15	0.12	0.10	0.05	0.08	0.06	0.04	0.03	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01																					
42		EFF = 83.2%			% DN = 21.6%			% UP = 78.4%			Lamp = (2) F32T8 SC (along, across, 45°) = N/A																																													
		0	0.83	0.83	0.83	0.74	0.74	0.74	0.56	0.56	0.56	0.39	0.39	0.39	0.24	0.24	0.24	0.17																																						
		1	0.76	0.73	0.70	0.67	0.65	0.62	0.49	0.48	0.46	0.35	0.34	0.33	0.22	0.21	0.21	0.15																																						
		2	0.70	0.64	0.59	0.62	0.57	0.53	0.44	0.41	0.39	0.31	0.30	0.28	0.20	0.19	0.18	0.13																																						
		3	0.64	0.57	0.51	0.56	0.50	0.46	0.39	0.36	0.33	0.28	0.26	0.24	0.18	0.17	0.16	0.12																																						
		4	0.58	0.50	0.44	0.52	0.45	0.40	0.35	0.31	0.28	0.25	0.23	0.21	0.16	0.15	0.14	0.10																																						
		5	0.54	0.45	0.39	0.47	0.40	0.35	0.31	0.27	0.25	0.23	0.20	0.18	0.15	0.13	0.12	0.09																																						
		6	0.49	0.40	0.34	0.44	0.36	0.31	0.28	0.24	0.21	0.20	0.18	0.16	0.13	0.12	0.11	0.08																																						
		7	0.46	0.36	0.30	0.40	0.32	0.27	0.25	0.22	0.19	0.19	0.16	0.14	0.12	0.11	0.10	0.07																																						
		8	0.42	0.33	0.27	0.37	0.29	0.24	0.23	0.19	0.17	0.17	0.15	0.13	0.11	0.10	0.09	0.07																																						
		9	0.39	0.30	0.24	0.35	0.27	0.22	0.21	0.17	0.15	0.16	0.13	0.11	0.10	0.09	0.08	0.06																																						
		10	0.37	0.27	0.22	0.32	0.24	0.20	0.19	0.16	0.13	0.14	0.12	0.10	0.10	0.08	0.07	0.06																																						
43		EFF = 85.2%			% DN = 28.7%			% UP = 71.3%			Lamp = (2) F32T8 SC (along, across, 45°) = N/A																																													
		0	3.87	0.87	0.87	0.78	0.78	0.78	0.61	0.61	0.61	0.45	0.45	0.45	0.31	0.31	0.31	0.24																																						
		1	3.80	0.77	0.74	0.72	0.69	0.66	0.54	0.53	0.51	0.41	0.40	0.39	0.29	0.28	0.28	0.22																																						
		2	0.73	0.68	0.63	0.66	0.61	0.57	0.48	0.46	0.44	0.37	0.35	0.34	0.26	0.25	0.24	0.20																																						
		3	0.67	0.60	0.55	0.60	0.54	0.50	0.43	0.40	0.37	0.33	0.31	0.29	0.24	0.23	0.22	0.18																																						
		4	0.62	0.54	0.48	0.55	0.49	0.43	0.39	0.35	0.32	0.30	0.28	0.26	0.22	0.20	0.19	0.16																																						
		5	0.57	0.48	0.42	0.51	0.44	0.38	0.35	0.31	0.28	0.27	0.25	0.23	0.23	0.18	0.17	0.14																																						
		6	0.53	0.43	0.37	0.47	0.39	0.34	0.32	0.28	0.25	0.25	0.22	0.20	0.18	0.17	0.15	0.13																																						
		7	0.49	0.39	0.33	0.44	0.36	0.30	0.29	0.25	0.22	0.23	0.20	0.18	0.17	0.15	0.14	0.11																																						
		8	0.45	0.35	0.29	0.41	0.32	0.27	0.26	0.22	0.20	0.21	0.18	0.16	0.15	0.14	0.12	0.10																																						
		9	0.42	0.32	0.26	0.38	0.30	0.24	0.24	0.20	0.18	0.19	0.16	0.14	0.14	0.13	0.11	0.09																																						
		10	0.39	0.30	0.24	0.35	0.27	0.22	0.22	0.18	0.16	0.18	0.15	0.13	0.13	0.12	0.10	0.09																																						
44		EFF = 88.3%			% DN = 40.3			% UP = 59.7			Lamp = (2) F32T8 SC (along, across, 45°) = N/A																																													
		0	0.93	0.93	0.93	0.84	0.84	0.84	0.69	0.69	0.69	0.55	0.55	0.55	0.42	0.42	0.42	0.36																																						
		1	0.85	0.82	0.79	0.77	0.75	0.72	0.61	0.60	0.58	0.49	0.48	0.47	0.38	0.37	0.37	0.31																																						
		2	0.78	0.72	0.67	0.71	0.66	0.62	0.54	0.51	0.49	0.44	0.42	0.40	0.34	0.33	0.32	0.27																																						
		3	0.71	0.64	0.58	0.65	0.58	0.53	0.48	0.45	0.42	0.39	0.37	0.34	0.31	0.29	0.28	0.24																																						
		4	0.65	0.57	0.50	0.60	0.52	0.46	0.43	0.39	0.36	0.35	0.32	0.30	0.28	0.26	0.24	0.21																																						
		5	0.60	0.50	0.44	0.55	0.46	0.40	0.39	0.34	0.31	0.32	0.28	0.26	0.25	0.23	0.21	0.18																																						
		6	0.55	0.45	0.38	0.50	0.42	0.36	0.35	0.30	0.27	0.28	0.25	0.23	0.23	0.20	0.19	0.16																																						
		7	0.51	0.41	0.34	0.47	0.38	0.32	0.32	0.27	0.24	0.26	0.23	0.20	0.21	0.18	0.16	0.14																																						
		8	0.47	0.37	0.30	0.43	0.34	0.28	0.29	0.24	0.21	0.24	0.20	0.18	0.19	0.16	0.15	0.13																																						
		9	0.44	0.34	0.27	0.40	0.31	0.25	0.26	0.22	0.19	0.22	0.18	0.16	0.17	0.15	0.13	0.11																																						

Figure 9-28 Continued

Typical Luminaire	Typical Intensity Distribution	pcc →	80			70			50			30			10			0
		pw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR ↓	Lamp = (2) F32T8 SC (along, across, 45°) = 1.2, 1.2, 1.3															
	6" square x-section, mostly downlight	0	0.61	0.61	0.61	0.59	0.59	0.59	0.54	0.54	0.54	0.50	0.50	0.50	0.46	0.46	0.46	0.44
	1	0.57	0.55	0.53	0.55	0.53	0.51	0.49	0.48	0.47	0.45	0.44	0.44	0.42	0.41	0.41	0.41	0.39
	2	0.53	0.49	0.46	0.51	0.48	0.45	0.44	0.42	0.40	0.41	0.39	0.38	0.38	0.37	0.36	0.34	0.34
	3	0.49	0.44	0.41	0.47	0.43	0.39	0.40	0.37	0.35	0.37	0.35	0.33	0.35	0.33	0.32	0.30	0.30
	4	0.45	0.40	0.36	0.43	0.38	0.35	0.36	0.33	0.31	0.34	0.31	0.29	0.32	0.30	0.28	0.27	0.27
	5	0.42	0.36	0.32	0.40	0.35	0.31	0.33	0.30	0.27	0.31	0.28	0.26	0.29	0.27	0.25	0.24	0.24
	6	0.39	0.33	0.29	0.37	0.32	0.28	0.30	0.27	0.24	0.28	0.25	0.23	0.26	0.24	0.22	0.21	0.21
	7	0.36	0.30	0.26	0.35	0.29	0.25	0.27	0.24	0.22	0.26	0.23	0.21	0.24	0.22	0.20	0.19	0.19
	8	0.34	0.27	0.23	0.32	0.27	0.23	0.25	0.22	0.19	0.24	0.21	0.19	0.22	0.20	0.18	0.17	0.17
	9	0.32	0.25	0.21	0.30	0.24	0.21	0.23	0.20	0.18	0.22	0.19	0.17	0.21	0.18	0.17	0.16	0.16
	10	0.30	0.23	0.19	0.29	0.23	0.19	0.21	0.18	0.16	0.20	0.18	0.16	0.19	0.17	0.15	0.14	0.14
	Completely indirect HID		EFF = 73% % DN = 90% % UP = 100% Lamp = M400/U (coated)* SC (along, across, 45°) = N/A															
	0	0.69	0.69	0.69	0.59	0.59	0.59	0.41	0.54	0.41	0.23	0.23	0.23	0.07	0.07	0.07	0.00	0.00
	1	0.63	0.60	0.58	0.54	0.52	0.43	0.35	0.34	0.33	0.20	0.20	0.19	0.06	0.06	0.06	0.00	0.00
	2	0.57	0.53	0.48	0.49	0.45	0.42	0.31	0.29	0.27	0.18	0.17	0.16	0.06	0.05	0.05	0.00	0.00
	3	0.52	0.46	0.41	0.45	0.39	0.36	0.27	0.25	0.23	0.16	0.14	0.13	0.05	0.05	0.01	0.00	0.00
	4	0.48	0.41	0.35	0.41	0.35	0.31	0.24	0.21	0.19	0.14	0.12	0.11	0.04	0.04	0.04	0.00	0.00
	5	0.44	0.36	0.31	0.37	0.31	0.26	0.21	0.18	0.16	0.12	0.11	0.10	0.04	0.04	0.03	0.00	0.00
	6	0.40	0.32	0.27	0.34	0.27	0.23	0.19	0.16	0.14	0.11	0.09	0.08	0.04	0.03	0.03	0.00	0.00
	7	0.37	0.29	0.23	0.31	0.25	0.20	0.17	0.14	0.12	0.10	0.08	0.07	0.03	0.03	0.02	0.00	0.00
	8	0.34	0.26	0.21	0.29	0.22	0.18	0.15	0.13	0.11	0.09	0.07	0.06	0.03	0.02	0.02	0.00	0.00
	9	0.31	0.23	0.18	0.27	0.20	0.16	0.14	0.11	0.09	0.08	0.07	0.05	0.03	0.02	0.02	0.00	0.00
10	0.29	0.21	0.16	0.25	0.18	0.14	0.13	0.10	0.08	0.07	0.06	0.05	0.02	0.02	0.02	0.00	0.00	
	Fluorescent cove with specular reflector		EFF = 71.6% % DN = 0.3% % UP = 99.7% Lamp = (1) F32T8 SC (along, across, 45°) = N/A															
	0	0.42	0.35	0.30	0.40	0.34	0.30	0.32	0.28	0.26	0.30	0.27	0.25	0.29	0.26	0.24	0.23	0.23
	1	0.40	0.32	0.28	0.38	0.31	0.27	0.30	0.26	0.24	0.28	0.25	0.23	0.27	0.24	0.22	0.21	0.21
	2	0.37	0.30	0.26	0.36	0.29	0.25	0.28	0.24	0.22	0.26	0.23	0.21	0.25	0.22	0.20	0.19	0.19
	3	0.35	0.28	0.24	0.34	0.27	0.23	0.26	0.22	0.20	0.25	0.22	0.19	0.23	0.21	0.19	0.18	0.18
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	0.67	0.67	0.67	0.64	0.64	0.64	0.58	0.58	0.58	0.53	0.53	0.53	0.48	0.48	0.48	0.46	0.46
	7	0.62	0.59	0.57	0.59	0.57	0.55	0.52	0.50	0.49	0.48	0.46	0.45	0.43	0.43	0.42	0.40	0.40
	8	0.57	0.53	0.50	0.55	0.51	0.48	0.47	0.45	0.43	0.43	0.41	0.40	0.40	0.38	0.37	0.35	0.35
	9	0.53	0.48	0.44	0.51	0.46	0.43	0.43	0.40	0.37	0.40	0.37	0.35	0.36	0.35	0.33	0.31	0.31
10	0.50	0.44	0.39	0.47	0.42	0.38	0.39	0.36	0.33	0.36	0.34	0.32	0.34	0.32	0.30	0.28	0.28	

Notes: EFF = efficiency; SC = spacing criteria.

For 6" reflector with PAR-38, multiply by 0.98.

For A12 lens, 2 × 4's, ratio of F40 to T8, 0.96, 0.94, and 0.89 for 2, 3, and 4-lamp versions.

For A12 lens, 2 × 4's, ratio of 2 to 3-lamp eff. = 1.05; ratio of 4 to 3-lamp eff. = 0.98.

For parabolics, 2 lamp versions have 12 cells, 4 lamp versions have 32 cells.

For 3" parabolic, 2 × 4's, ratio of 2 to 3-lamp eff. = 1.06; ratio of 4 to 3-lamp eff. = 0.96.

For 4" parabolic, 2 × 4's, ratio of 2 to 3-lamp eff. = 0.98; ratio of 4 to 3-lamp eff. = 0.90.

CUs do not consider shadowing of the lighting fixture or cove.

* Different lamp types have been considered in determining the listed photometric report.

and

average initial ceiling cavity exitance

= total bare-lamp lumens

$$\times \frac{\text{ceiling cavity exitance coefficient}}{\text{floor area}} \quad (9-60)$$

If the maintained average wall exitance or the maintained average ceiling cavity exitance is required, a light loss factor is introduced into these equations in the same manner as for maintained average illuminance. For suspended luminaires the average ceiling cavity exitance obtained is the average exitance of the imaginary plane at the level of the lumi-

nares. This exitance does not include the weighted average exitance of the luminaires as seen from below. It is rather the average exitance of the background against which the luminaires are seen. In the case of recessed or ceiling-mounted luminaires, the average ceiling cavity exitance obtained is the average exitance of the ceiling between luminaires.

Limitations. The limitations for exitance calculations are similar to those for average illuminance. In addition, the wall reflectance used to enter the tables is a weighted average of the reflectances for the various parts of the walls; the wall exitance found from the wall exitance coefficient is the value that would occur if the walls were of a uniform and perfectly diffuse reflectance equal to the average reflectance

Figure 9-29. Multiplying Factors for Effective Floor Cavity Reflectances Other Than 20% (0.2)

% Effective Ceiling Cavity Reflectance, ρ_{cc}	80				70				50			30			10		
	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
For 30% Effective Floor Cavity Reflectance (20% = 1.00)																	
Room Cavity Ratio																	
1	1.092	1.082	1.075	1.068	1.077	1.070	1.064	1.059	1.049	1.044	1.040	1.028	1.026	1.023	1.012	1.010	1.008
2	1.079	1.066	1.055	1.047	1.068	1.057	1.048	1.039	1.041	1.033	1.027	1.026	1.021	1.017	1.013	1.010	1.006
3	1.070	1.054	1.042	1.033	1.061	1.048	1.037	1.028	1.034	1.027	1.020	1.024	1.017	1.012	1.014	1.009	1.005
4	1.062	1.045	1.033	1.024	1.055	1.040	1.029	1.021	1.030	1.022	1.015	1.022	1.015	1.010	1.014	1.009	1.004
5	1.056	1.038	1.026	1.018	1.050	1.034	1.024	1.015	1.027	1.018	1.012	1.020	1.013	1.008	1.014	1.009	1.004
6	1.052	1.033	1.021	1.014	1.047	1.030	1.020	1.012	1.024	1.015	1.009	1.019	1.012	1.006	1.014	1.008	1.003
7	1.047	1.029	1.018	1.011	1.043	1.026	1.017	1.009	1.022	1.013	1.007	1.018	1.010	1.005	1.014	1.008	1.003
8	1.044	1.026	1.015	1.009	1.040	1.024	1.015	1.007	1.020	1.012	1.006	1.017	1.009	1.004	1.013	1.007	1.003
9	1.040	1.024	1.014	1.007	1.037	1.022	1.014	1.006	1.019	1.011	1.005	1.016	1.009	1.004	1.013	1.007	1.002
10	1.037	1.022	1.012	1.006	1.034	1.020	1.012	1.005	1.017	1.010	1.004	1.015	1.009	1.003	1.013	1.007	1.002
For 10% Effective Floor Cavity Reflectance (20% = 1.00)																	
Room Cavity Ratio																	
1	.923	.929	.935	.940	.933	.939	.943	.948	.956	.960	.963	.973	.976	.979	.989	.991	.993
2	.931	.942	.950	.958	.940	.949	.957	.963	.962	.968	.974	.976	.980	.985	.988	.991	.995
3	.939	.951	.961	.969	.945	.957	.966	.973	.967	.975	.981	.978	.983	.988	.988	.992	.996
4	.944	.958	.969	.978	.950	.963	.973	.980	.972	.980	.986	.980	.986	.991	.987	.992	.996
5	.949	.964	.976	.983	.954	.968	.978	.985	.975	.983	.989	.981	.988	.993	.987	.992	.997
6	.953	.969	.980	.986	.958	.972	.982	.989	.977	.985	.992	.982	.989	.995	.987	.993	.997
7	.957	.973	.983	.991	.961	.975	.985	.991	.979	.987	.994	.983	.990	.996	.987	.993	.998
8	.960	.976	.986	.993	.963	.977	.987	.993	.981	.988	.995	.984	.991	.997	.987	.994	.998
9	.963	.978	.987	.994	.965	.979	.989	.994	.983	.990	.996	.985	.992	.998	.988	.994	.999
10	.965	.980	.989	.995	.967	.981	.990	.995	.984	.991	.997	.986	.993	.998	.988	.994	.999
For 0% Effective Floor Cavity Reflectance (20% = 1.00)																	
Room Cavity Ratio																	
1	.859	.870	.879	.886	.873	.884	.893	.901	.916	.923	.929	.948	.954	.960	.979	.983	.987
2	.871	.887	.903	.919	.886	.902	.916	.928	.926	.938	.949	.954	.963	.971	.978	.983	.991
3	.882	.904	.915	.942	.898	.918	.934	.947	.936	.950	.964	.958	.969	.979	.976	.984	.993
4	.893	.919	.941	.958	.908	.930	.948	.961	.945	.961	.974	.961	.974	.984	.975	.985	.994
5	.903	.931	.953	.969	.914	.939	.958	.970	.951	.967	.980	.964	.977	.988	.975	.985	.995
6	.911	.940	.961	.976	.920	.945	.965	.977	.955	.972	.985	.966	.979	.991	.975	.986	.996
7	.917	.947	.967	.981	.924	.950	.970	.982	.959	.975	.988	.968	.981	.993	.975	.987	.997
8	.922	.953	.971	.985	.929	.955	.975	.986	.963	.978	.991	.970	.983	.995	.976	.988	.998
9	.928	.958	.975	.988	.933	.959	.980	.989	.966	.980	.993	.971	.985	.996	.976	.988	.998
10	.933	.962	.979	.991	.937	.963	.983	.992	.969	.982	.995	.973	.987	.997	.977	.989	.999

used. Thus, many parts of the wall may have exitance values that differ from the calculated average value. A correction can be applied to determine the approximate exitance of any part of the wall. For any area on the wall,

exitance =

$$\frac{(\text{average wall exitance}) \times (\text{reflectance of area})}{\text{average wall reflectance}} \quad (9-61)$$

The Lumen Method Applied to Partitioned Spaces

The lumen method can be applied to partitioned spaces by separating the room cavity into both an upper cavity that extends from the top of the partitions to the luminaire plane, and a second cavity that is the cavity within the partitioned area. The upper cavity has an area that is equal to the area of the room, and the lower cavity covers only the area included

within a single partitioned zone. Two lumen method calculations need to be made in order to perform a complete analysis (see Example 1 in “Examples of Basic Lighting Calculations,” in this chapter).

First, the calculation is performed for the upper cavity to determine the illuminance falling on the top of the partitions. The floor cavity for this analysis is the area below the top of the partitions, and the effective floor cavity reflectance is that of a single partitioned space as viewed from above. All of the room’s luminaires are used in this analysis, since presumably they all contribute to the illuminance on the plane at the top of the partitions. The CU is determined for the appropriate cavity ratio, and the average illuminance on the top of the partitions is then determined.

Next, the coefficient of utilization for the lower cavity, the area within a single partition, is considered. The coefficient of utilization is determined for a virtual luminaire that has a lambertian distribution, using Figure 9-30. The appropriate wall and effective floor cavity reflectances are used to obtain this value. The effective ceiling cavity reflectance assumed in this table is zero, since interreflections between the upper and lower room cavities were already considered in the determination of the illuminance on the top of the partitions. In many partitioned spaces, each cubicle has only three sides formed by the partitions, with the fourth side being open. For the wall reflectance, an area-weighted average of the cubicle walls should be used, where the opening is assigned a reflectance of zero. The illuminance obtained at the top of the partitions is then multiplied by the coefficient of utilization obtained for the cubicle area to obtain the average illuminance on the workplane. The equation is summarized below:

$$E = \frac{\left(\begin{array}{c} \text{total bare} \\ \text{lamp lumens} \end{array} \right) \times \text{CU}_{\text{upper cavity}} \times \text{CU}_{\text{cubicle}} \times \text{LLF}}{\text{area of workplane}} \quad (9-62)$$

This procedure is likely to be more accurate for indirect lighting systems than for direct, since the procedure assumes that flux is entering the partition from above in a perfectly diffuse manner. Luminaires that direct light predominantly downward are likely to exhibit slightly higher illuminance values than this procedure determines.

CALCULATION OF EQUIPMENT-RELATED QUANTITIES

So far in this chapter, quantities that characterize the lighting within a room have been discussed. Another set of quantities characterizes the luminaire. These include coefficients of utilization, optical efficiency, and the spacing criterion.

Lumen Method Coefficients of Utilization^{31,45,82-84}

CU tables, wall exitance coefficients, and ceiling cavity exitance coefficients can be prepared. It is desirable to have standard tables for these values to prevent misunderstandings and to facilitate direct comparisons of the data for different luminaires. These coefficients are derived from the equations described in the above section, “Basic Principles.” There are five basic assumptions used to develop the zonal-cavity coefficients:

- Room surfaces are lambertian reflectors.
- The incident flux on each surface is uniformly distributed over that surface.
- The luminaires are uniformly distributed throughout the room (uniformly dense but not necessarily in a uniform pattern).
- The room is empty.
- The room surfaces are spectrally neutral.

Figure 9-28 shows the recommended form for unabridged CU tables. It is recognized that space limitations often necessitate abridgements. In that case, only the columns for $\rho_{CC} = 80, 50,$ and 10% are recommended for luminaires having 0 to 35% of their output in the 90 to 180° zone; and 80, 70, and 50% for luminaires having over 35% of their output in that zone. Also, the $\rho_{CC} = 10\%$ columns are not required for abridged tables. It is recommended that CUs be published to two decimal places, wall exitance coefficients to three decimal places, and ceiling cavity exitance coeffi-

Figure 9-30. Coefficients of Utilization for a Perfectly Diffuse Emitter

Floor Cavity Reflectance ($\rho_{cc} = 20\%$)					
Wall Reflectance ρ_w (Percent)	70	50	30	10	0
RCR					
0	1.00	1.00	1.00	1.00	1.00
1	.90	.88	.86	.84	.84
2	.81	.77	.74	.71	.70
3	.74	.69	.64	.61	.59
4	.67	.61	.56	.52	.50
5	.61	.54	.49	.44	.42
6	.56	.44	.43	.38	.36
7	.52	.44	.38	.33	.31
8	.48	.39	.33	.29	.27
9	.44	.35	.29	.25	.23
10	.41	.32	.26	.22	.20

cients to three decimal places. A wall direct radiation coefficient (WDRC) should be published to three decimal places for every room cavity ratio, adjacent to the wall exitance coefficient table. The three significant figures are not justified in terms of coefficient accuracy but are required because certain computational methods require the small differences between these coefficients.

Computation

1. Define 18 conic solid angle zones of 10° width from the nadir to the zenith about the luminaire as shown in Figure 9-31, where the index of each zone, N , is an integer between 1 and 18 inclusive.
2. Determine the flux Φ_N (lumens) in the various zones:
 - a. The flux in a conic solid angle (Figure 9-32) is given by

$$\Phi_N = 2\pi I_{\theta_N} (\cos(\theta_N) - \cos(\theta_{N+1})) \quad (9-63)$$

where

I_{θ_N} = midzone intensity, in cd, for the N th zone,
 θ_N, θ_{N+1} = bounding cone angles.

- b. If the intensity is not rotationally symmetric about the vertical axis, average the intensity about the vertical axis at each vertical angle θ . Note that the intensity must be sampled at equal angular intervals about the vertical axis. For example, if the intensity is known for three vertical planes [$I_{\theta, 90^\circ}$ (perpendicular), $I_{\theta, 45^\circ}$ and $I_{\theta, 0^\circ}$ (parallel)], then

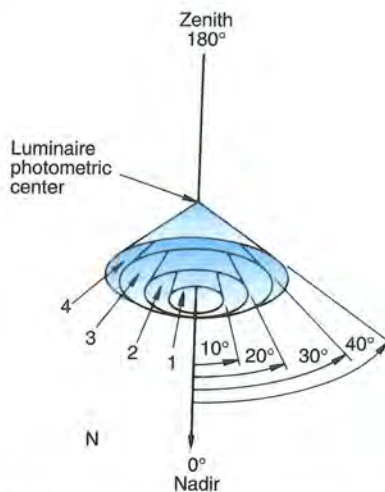


Figure 9-31. Conic solid angle zones of 10° width for use in calculating zonal flux.

$$I_\theta = \frac{1}{4} (I_{\theta, 0^\circ} + 2I_{\theta, 45^\circ} + I_{\theta, 90^\circ}) \quad (9-64)$$

Although three planes are sufficient for luminaires of nominal rotational symmetry, photometric data at 15° or 22.5° increments about the vertical axis are preferred for luminaires without this symmetry.

- c. If the intensity is taken at 10° vertical intervals ($\theta = 5^\circ, 15^\circ, 25^\circ, \dots$), then the flux Φ_N is determined by the application of the equation in part (a), above, to the full zone. It is preferred to have intensity values at 5° vertical angles ($\theta = 2.5^\circ, 7.5^\circ, 12.5^\circ, \dots$). Then zone N is divided into two parts, the equation is applied to each part, and the resulting flux is summed.

3. Determine the additional flux functions:

$$\Phi_{\text{luminaire}} = \sum_{N=1}^{18} \Phi_N \quad (9-65)$$

$$\eta_{\text{down}} = \frac{1}{\Phi_{\text{lamps}}} \sum_{N=1}^9 \Phi_N \quad (9-66)$$

$$\eta_{\text{up}} = \frac{1}{\Phi_{\text{lamps}}} \sum_{N=10}^{18} \Phi_N \quad (9-67)$$

where

- Φ_{lamps} = total flux emitted by the lamps,
- $\Phi_{\text{luminaire}}$ = total flux emitted by the luminaire,
- η_{down} = proportion of lamp flux leaving the luminaire in a downward direction,
- η_{up} = proportion of lamp flux leaving the luminaire in an upward direction.

4. Determine the direct ratio, D_{RCR} , related to the fraction of luminaire flux below the horizontal that is directly incident on the workplane:

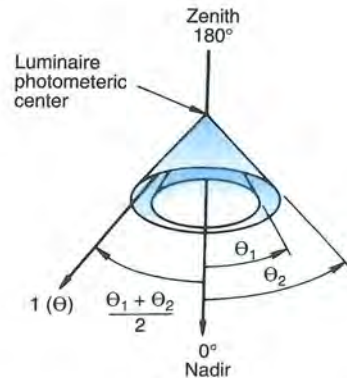


Figure 9-32. Angles used in calculating zonal flux.

$$D_{RCR} = \frac{1}{\eta_{down} \Phi_{lamps}} \sum_{N=1}^9 K_{RCR,N} \Phi_N \quad (9-68)$$

where

RCR = room cavity ratio, used here as an integer between 1 and 10 inclusive,

$K_{RCR,N}$ = zonal multipliers.

The zonal multiplier is the fraction of downward-directed flux directly incident on the workplane (lower surface of room cavity) for each zone N . The zonal multipliers are functions of the RCR:

$$K_{RCR,N} = e^{-A \cdot RCR^B} \quad (9-69)$$

where A and B are constants and are given in Figure 9-33.

5. Determine the parameters C_1 , C_2 , C_3 , and C_0 as an intermediate step. In the formulas below, ρ_w is the wall reflectance, ρ_{CC} is the ceiling cavity reflectance, and ρ_{FC} is the floor cavity reflectance, which is taken as 0.2 for standard coefficient tables. $F_{CC \rightarrow FC}$ is the form factor from the ceiling cavity to the floor cavity, described above in the discussion of flux transfer theory in the above section, "Basic Principles":

$$C_1 = \frac{(1 - \rho_w)(1 - f_{CC \rightarrow FC}^2)RCR}{2.5\rho_w(1 - f_{CC \rightarrow FC}^2) + RCR f_{CC \rightarrow FC}(1 - \rho_w)} \quad (9-70)$$

$$C_2 = \frac{(1 - \rho_{CC})(1 + f_{CC \rightarrow FC})}{1 + \rho_{CC} f_{CC \rightarrow FC}} \quad (9-71)$$

$$C_3 = \frac{(1 - \rho_{FC})(1 + F_{CC \rightarrow FC})}{1 + \rho_{FC} f_{CC \rightarrow FC}} \quad (9-72)$$

$$C_0 = C_1 + C_2 + C_3 \quad (9-73)$$

Figure 9-33. Constants for the Zonal Multiplier Equation

Zone (N)	A	B
1	0	0
2	0.041	0.98
3	0.070	1.05
4	0.100	1.12
5	0.136	1.16
6	0.190	1.25
7	0.315	1.25
8	0.640	1.25
9	2.10	0.80

6. Determine the coefficient of utilization (CU), the wall exitance coefficient (WEC), and the ceiling cavity exitance coefficient (CCEC) for each applicable combination of reflectances and RCR:

$$CU = \frac{2.5\rho_w C_1 C_3 (1 - D_{RCR}) \eta_{down}}{RCR (1 - \rho_w) (1 - \rho_{FC}) C_0} + \frac{\rho_{CC} C_2 C_3 \eta_{up}}{(1 - \rho_{CC}) (1 - \rho_{FC}) C_0} \left(1 - \frac{\rho_{FC} C_3 (C_1 + C_2)}{(1 - \rho_{FC}) C_0} \right) \frac{D_{RCR} \eta_{down}}{1 - \rho_{FC}} \quad (9-74)$$

$$WEC = \frac{2.5\rho_w (1 - D_{RCR}) \eta_{down}}{RCR (1 - \rho_w)} \times \left(1 - \frac{2.5\rho_w C_1 (C_2 + C_3)}{RCR (1 - \rho_w) C_0} \right) + \frac{2.5\rho_w \rho_{CC} C_1 C_2 \eta_{up}}{RCR (1 - \rho_w) (1 - \rho_{CC}) C_0} + \frac{2.5\rho_w \rho_{FC} C_1 C_3 D_{RCR} \eta_{down}}{RCR (1 - \rho_w) (1 - \rho_{FC}) C_0} \quad (9-75)$$

$$CCEC = \frac{2.5\rho_w \rho_{CC} C_1 C_2 (1 - D_{RCR}) \eta_{down}}{RCR (1 - \rho_w) (1 - \rho_{CC}) C_0} + \frac{\rho_{CC} \eta_{up}}{1 - \rho_{CC}} \left(1 - \frac{\rho_{CC} C_2 (C_1 + C_3)}{(1 - \rho_{CC}) C_0} \right) + \frac{\rho_{CC} \rho_{FC} C_2 C_3 D_{RCR} \eta_{down}}{(1 - \rho_{CC}) (1 - \rho_{FC}) C_0} \quad (9-76)$$

7. Determine the wall direct radiation coefficient (WRDC) for each RCR:

$$WRDC = \frac{2.5 \eta_{down} (1 - D_{RCR})}{RCR} \quad (9-77)$$

8. The above equations can be used to calculate the CU, WEC, and CCEC when the RCR equals zero, but the forms of the equations must be arranged to avoid division by zero. It is simplest to use the following relationships:

$$CU_{RCR=0} = \frac{\eta_{down} + \rho_{CC}\eta_{up}}{1 - \rho_{CC}\rho_{FC}} \quad (9-78)$$

$$CCEC_{RCR=0} = \frac{\rho_{CC}(\eta_{up} + \rho_{FC}\eta_{down})}{1 - \rho_{CC}\rho_{FC}} \quad (9-79)$$

Luminaire Efficiency

The luminaire efficiency is simply the ratio of the lumens leaving the luminaire to the total lumens produced by the lamps. From the expressions above, this quantity is

$$\text{luminaire efficiency} = \frac{\Phi_{\text{luminaire}}}{\Phi_{\text{lamps}}} \quad (9-80)$$

The luminaire efficiency is considered in the determination of the CU.

Average Luminaire Luminance

The average luminaire luminance is a means of evaluating the effect that a luminaire has on visual comfort, as well as veiling reflections on task surfaces such as VDTs. A value can be easily determined in any direction, given the photometric characteristics of the luminaire. Since luminance is expressed in candelas per unit area, the average luminance in a direction (θ, ψ) (specified in spherical coordinates) is

$$L(\theta, \psi)_{\text{avg}} = \frac{I(\theta, \psi)}{A_{\text{luminaire}} \cos \theta} \quad (9-81)$$

where

$I(\theta, \psi)$ = intensity of the luminaire in the direction (θ, ψ) ,
 $A_{\text{luminaire}}$ = surface area of the luminous element(s) of the luminaire.

Luminaire Spacing Criterion

The luminaire spacing criterion⁸⁵ (SC) is a classification technique for interior luminaires relating to the spread or distribution of the direct illuminance on a horizontal plane. It tests the uniformity of horizontal illuminance at two pairs of selected points to estimate the probable extreme limit of acceptable luminaire spacing. It is not a specification of the spacing-to-mounting-height ratio to be used in a lighting installation, and in fact, installation of luminaires at this nominal value may produce a poor lighting system.

The purpose of this classification technique is to aid designers in rapidly assessing one aspect of the potential of a luminaire with respect to its applications. It gives some idea about the distribution of flux from a luminaire and its subsequent effect on lighting system parameters, using only a single number. The basis of the luminaire spacing criterion is the horizontal illuminance on the workplane due to direct illuminance from nearby luminaires. As a first approximation, it is assumed that this represents a limiting case, since the reflected component of illuminance and the illuminance due to more distant luminaires generally increases the uniformity of horizontal illuminance from point to point.

When two similar conventional luminaires are near their maximum spacing, the illuminance directly under a luminaire (P) is principally due to the overhead luminaire (A) (Figure 9-34a). Further, a very probable point of low illuminance is at the midpoint between two luminaires (Q). The maximum spacing at a given mounting height above the workplane is chosen such that the illuminance halfway between the two luminaires (Q) due to both luminaires (A and B) equals the illuminance under one (P) due to that one luminaire (A) only. Another likely point for low illuminance is at the center of a square array of adjacent luminaires (Figure 9-34b). The maximum spacing at a given mounting height above the workplane is chosen such that

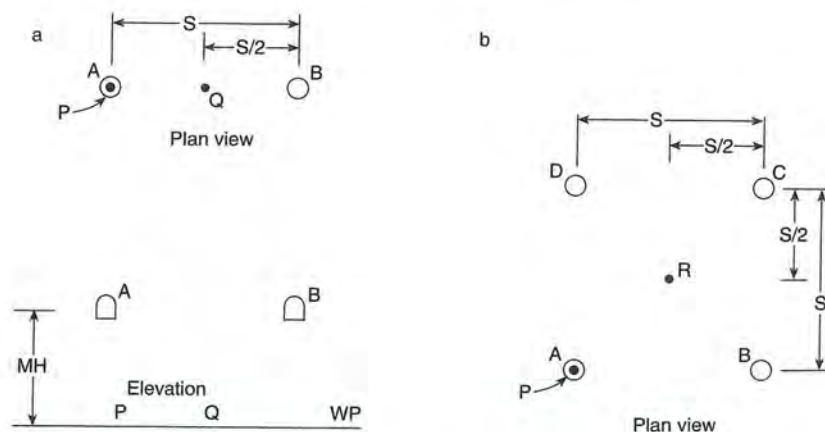


Figure 9-34. Points Q and R represent points of most probable low illuminance for (a) a configuration of 2 luminaires, and (b) a square array of 4 luminaires.

the illuminance at the center of the luminaires (R) due to all four luminaires (A , B , C , and D) equals the illuminance under one (P) due to that one luminaire (A) only. The maximum spacing (expressed as a spacing-to-mounting-height ratio that is unitless) that fulfills each of the above conditions is easily determined on a special graph (Figure 9-35) using the intensity distribution of the luminaire. For the purpose of establishing this criterion, it is assumed that the inverse square law is valid. This is the only assumption for the computations.

Procedure. The procedure for calculating the luminaire spacing criterion is as follows:

- A. For luminaires whose intensity distribution is nominally symmetric about the nadir:
 1. Plot the relative intensity of the luminaire on the chart of Figure 9-35.
 2. Locate the point of one-half the intensity at 0° on the ordinate, and draw a line through that point and parallel to the diagonal lines. If the intensity varies significantly in the vicinity of 0° , use an average of the intensity over the 0 to 5° polar angle.
 3. Read scale A above the intersection of this line with the intensity curve.
 4. Repeat step 2 using the point of one-quarter the intensity at 0° .
 5. Read scale B above the intersection of this line with the intensity curve.
 6. The lower of the values found in steps 3 and 5 is the luminaire spacing criterion. Round off the value to the nearest 0.1.

- B. For luminaires with significantly asymmetric intensity distributions about the nadir:

1. Independently evaluate the intensity distributions in the parallel and perpendicular (0° and 90°) planes.
2. Apply steps 1, 2, and 3 from part A above for each of the intensity curves. Round off to the nearest 0.1.
3. In some cases, it may be appropriate to evaluate the intensity distribution in the 45° plane.

Interpretation. The value from scale A corresponds to the luminaire spacing criterion at point Q (Figure 9-34a), and the value from scale B corresponds to this criterion at point R (Figure 9-34b). Thus for symmetrical intensity distributions, the luminaire spacing criterion requires the direct horizontal illuminance at both test points to be equal to or greater than the illuminance directly below a single luminaire. For non-symmetrical intensity distributions, it is generally found that independent testing at point Q for each orientation is adequate. A point directly under a luminaire has relatively high illuminance and receives its principal contribution from the luminaire overhead when the spacing is large. If the illuminance at a probable low point due to the closest luminaires is no lower than that at a probable high point, due to the main component, then it is likely that reasonable uniformity is achieved over the entire workplane. The luminaire spacing criterion only suggests a maximum spacing at which the horizontal illuminance is reasonably uniform. When other criteria are considered, such as overlap between luminaires, vertical illuminance, shadowing, and illuminance distribution above the workplane, it generally is found that luminaires

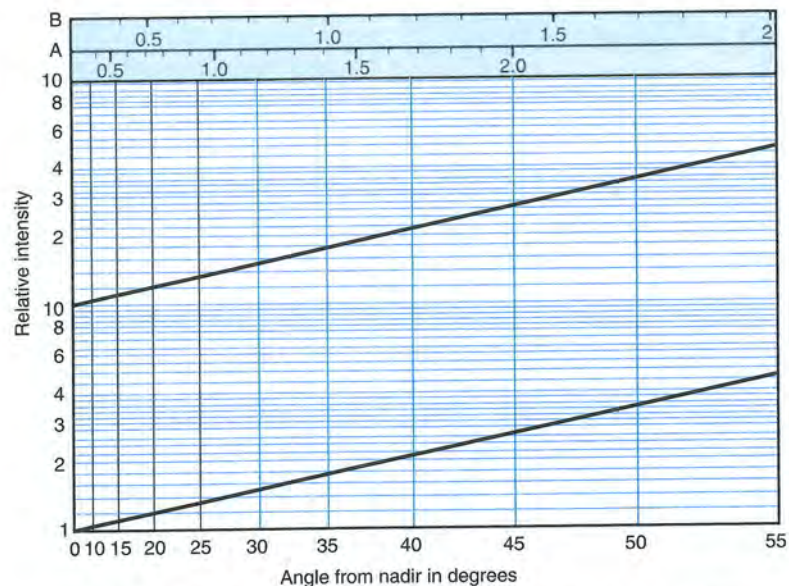


Figure 9-35. Chart for determining the luminaire spacing criterion.

must be installed at some spacing-to-mounting-height ratio less than the value of the luminaire spacing criterion.

In cases where uniformity is particularly important, the lighting designer must calculate the illuminance at several points throughout the room. It is suggested that a maximum value of 1.5 be assigned as the luminaire spacing criterion for any luminaire, since the use of larger values frequently does not produce acceptable lighting installations when all performance criteria are examined. Also, certain luminaires are designed to be installed only with specific spacing relations, and neither larger nor smaller spacings are desirable. In such cases, a luminaire spacing criterion is not applicable. Specific limits or ranges for the spacing-to-mounting-height ratios should be recommended by the manufacturer, and the basis for the recommendation should be stated, such as a certain degree of horizontal illuminance uniformity (determined by point calculations). In addition to the luminaire spacing criterion, it is possible to determine illuminance uniformity for specific installation conditions and report spacing-to-mounting-height limits for such conditions. If that is done, the luminaire layout, the room conditions, the uniformity criteria, and any application restrictions should be explicitly described.

INTERPRETATION AND LIMITS OF CALCULATED QUANTITIES

Calculated quantities can be used to provide the designer of a lighting system with information that could not otherwise be obtained except with an actual mock-up of a lighting installation. Information on illuminance, luminance, exitance, contrast, visual comfort probability, visibility, and visual performance metrics can be used to compare alternative designs and to verify that design criteria are met. These calculated quantities can also be used to protect or challenge a specification. Calculations are often required to meet strict design requirements imposed by labor unions, owners, local codes, or the like. If used correctly, computer models can be a valuable asset in designing a lighting system to meet particular design criteria.

With recent advances in the field of computer graphics, it is now possible to view the effects of a lighting system on a room through a computer-generated rendering of a space. At the heart of these renderings is a complex lighting analysis. The transformation from luminance data to a realistic-looking synthetic image requires special attention, since a computer screen has a limited range of available luminances. These tools are now being used by lighting professionals to evaluate and market their designs. Further improvements in this process will certainly make computer-generated visual methods more popular in the future.

In reviewing any lighting calculations, the results should first be screened for possible errors. Improper orientation or placement of a luminaire may produce incorrect results. Im-

proper photometry, lamp lumen output, or light loss factors may also cause errors. If the results appear unreasonable, an error may be producing an inaccurate result. Assuming that the results are for the proper arrangement of lighting equipment and room surfaces, some advice is provided below to help evaluate computer output.

Illuminance

Often a designer has selected a target illuminance, and a detailed analysis is performed to determine if the target value is provided. For maintained illuminance, a design is generally acceptable if the illuminance is within 10% of the target value. For energy conservation purposes, values below the target value are preferred over values above.

It is difficult, however, to achieve a uniform value everywhere within a space, or even across a desk or workplane. A 15% variation in illuminance is generally considered to be tolerable. In all cases it is the responsibility of the designer to determine if a particular variation is acceptable.

In evaluating illuminance, it is important to focus on the actual task locations. Most general lighting systems provide a higher illuminance in the middle of the room than near the walls. If the principal task locations are against the walls, a more detailed analysis may be needed to properly evaluate the illuminance at those areas.

Obstructions in a space, such as partitions, should be considered in a lighting calculation model if possible. If an empty room is modeled, the illuminance near a vertical partition is likely to be much lower than predicted.

Luminance

Luminances can be used to evaluate the appearance of a space. Scallop, sharp luminaire cutoffs, and the general pattern of brightnesses can be studied through numerical and graphical models. Computer renderings or simple luminance contours for room surfaces can provide the needed information for a designer to evaluate the performance of lighting equipment.

Luminances can also be evaluated with respect to a luminance ratio criterion. In the lighting of spaces containing VDTs, the uniformity of the luminance on the ceiling and the maximum ceiling luminance are critical aspects to study (see Chapter 11, Office Lighting).

Contrast

The calculation of task contrast, particularly for specular tasks, provides an indication of where veiling reflections occur within a space. Contrast can also be used to compare the performance of two different lighting systems. Visibility and visual performance metrics that use task contrast can provide some insight into the significance of the contrast and the task luminance provided by a lighting system.

Visual Comfort Probability

Visual comfort probability (VCP) is a metric with limited application. It was developed for lensed fluorescent lighting equipment. It is not valid for use with incandescent or HID equipment. It also cannot be used with luminaires that have an upward component. The procedure has never been proven to accurately model the discomfort caused by parabolic fluorescent luminaires, although many lighting professionals continue to apply it in such situations. Parabolic luminaires are much less uniform in luminance than lensed luminaires, and the difference can have a noticeable effect on the comfort of occupants.

Small differences in VCP are not significant. VCP differences of less than 5 points do not indicate a meaningful difference in discomfort glare potential.

Comparison of Calculated and Measured Quantities

Although it seems reasonable to expect calculated values of quantities to be reproduced in the field, in practice it is very difficult to reconcile measured quantities with those provided by calculation. Assumptions inherent in any calculation model often represent conditions very different from those in an actual lighting installation.¹ Some of these conditions are listed below:

- Lambertian surfaces are assumed in most computer programs. Real-world surfaces may contain some degree of specularity.
- The room surface reflectance input to analysis software may not accurately represent what is present in the field.
- Reduced electrical voltage in the power system may produce reduced light output.
- The assumed ballast factor may be much different from that present in the field.
- Thermal effects in an installed luminaire may alter light output.
- Minor differences incurred in the manufacturing process or in the positioning of the lamp within a luminaire may alter the luminaire's photometric distribution.

Furniture and other absorbing and reflecting surfaces may not have been considered in the computer model. No analysis model is an exact representation of any real room. Simplifying assumptions in the calculation method may limit the accuracy of the results. Far-field photometric methods applied in a near-field situation may not accurately model the luminaire performance.

Another reason for disagreement can be errors in the measurement process. It is important to follow strict guidelines when measuring the photometric performance of light-

ing systems. For example, it is important that the lighting system be measured at a temperature that is representative of its thermal equilibrium condition. New lamps should operate for at least 100 h before measurements are taken. The operator of a photometer must ensure that his or her own presence does not influence the reading. Orientation and positioning of the photometer are also critical; a tripod with a leveling device is particularly useful when conducting horizontal illuminance measurements. Finally, all daylight should be eliminated from the measurements on interior lighting systems, perhaps by conducting measurements at night. Any attempt to subtract out daylight levels is difficult and is likely to introduce errors because of the temporal variations in daylight illuminance.

The magnitude of the differences between detailed analysis methods and field measurements varies. In general, differences of less than 20% can be expected, but in extreme cases, where a calculation method simply cannot handle the complexity of the lighting system, they may be greater. For a more complete discussion of the uncertainties, see reference 83.

EXAMPLES OF BASIC LIGHTING CALCULATIONS

The purpose of this section is to show how to apply some of the equations and procedures described in previous sections to lighting problems. Seven practical lighting problems demonstrate the calculation of basic quantities. With the exception of visual task contrast, the calculation of derived quantities is not demonstrated, nor are equipment-related quantities calculated, because these are normally calculated by manufacturers of lighting equipment.

The following outline helps organize the basic lighting calculation procedures and in fact represents the order in which basic calculations are often performed.

First-order calculations: illuminance

1. Direct calculations
 - A. Diffuse, lambertian emission
 - B. Real (nondiffuse) emission distributions
2. Interreflection calculations

Second-order calculations: luminance

1. Diffuse, lambertian reflection
2. Real, (bidirectional) reflectance distributions

The first-order calculations are used to characterize the light reaching a surface, that is, the illuminance. The illuminance on a surface is a result of the light reaching that surface directly and by interreflections from surrounding surfaces. Luminance describes how light makes objects and surfaces appear and includes determination of contrast and luminance ratios. The determination of luminance is a second-order calculation because it almost always follows an illuminance calculation.

The first-order (illuminance) calculations are of two types. The first type is used to determine how much light reaches a surface or a point directly from a luminous source. The second type is used to determine how much light reaches the same surface or point from a secondary source of light that is, in fact, luminous by reflection.

Direct illuminance, either averaged over a surface or at a point on a surface, is treated as if produced by light emitted directly from a point source (as in the case of an incandescent lamp downlight), a line source (a narrow fluorescent lamp luminaire), or an area source (a window). These direct illuminance calculations assume one of two types of emitters, diffuse or nondiffuse.

Diffuse emitters are idealized approximations of reality that make calculations simpler to perform. Such emitters follow Lambert's cosine law of emission. This approximation is useful and appropriate for some reflective materials, such as cloth-covered partitions and flat-latex-painted walls, and for some transmissive materials, such as the face of a white plastic sign. Some self-luminous sources, such as the surface of a fluorescent lamp, can also be considered diffuse emitters.

Nondiffuse emitters have specific luminous intensity distributions determined by photometric measurement. In this section, they are referred to as real emitters. Luminaires are almost always treated as real emitters.

Interreflection is the repeated reflection of light among surfaces. For interreflection calculations, surfaces are always assumed to be diffuse reflectors. These surfaces are of finite area, their number and sizes dictated by the accuracy needed for the calculation. More surfaces of smaller size are specified for more accurate interreflection calculations. Interreflection calculations lead to surface exitance values, which are then used as sources of illumination. These values produce a quantity called the interreflected component in the illuminance calculation.

For some illuminance calculations, such as those for an indirect electric lighting system, only the interreflections are relevant. For some direct lighting systems, interreflections are negligible contributors to the total illuminance; in these cases, an experienced designer does not bother to calculate them (see the section "Characterizing Light for Calculation Purposes").

The second-order (luminance) calculations in this section are for luminance produced by reflection. That is, once light reaches a surface, the reflection characteristics of the surface determine its luminance. There are two types of luminance calculations: those for surfaces that can be approximated by diffuse reflection (that is, those that follow Lambert's cosine law of reflection), and those requiring specificity as to the bidirectional reflectance characteristics of the surface. Bidirectionality means that the reflectance of the surface depends on both the incident and the exitant directions of light. All real surfaces are characterized by a bidirectional reflectance distribution function (BRDF). Luminance calcu-

lations for real surfaces are the only ones for which the direction of incident light is important. Luminance by transmission is not considered in this section.

A General Algorithm for Lighting Calculations

The following discussion presents a general algorithm for lighting calculations. It consists of six steps:

1. Determine the quantity to be calculated.
2. Identify luminaires and the information describing them.
3. Determine the accuracy, complexity, and detail of the calculation.
4. Identify required geometric, reflectance, and other ancillary data.
5. Determine the appropriate equations or computational procedure.
6. Solve the equations or complete the procedure.

1. Determine the Quantity to Be Calculated. An evaluation of the proposed lighting system is the first step in the lighting calculation process. This evaluation includes a determination of what needs to be calculated and the required accuracy of the calculation. Listed in order of increasing complexity are the quantities considered in this section of example calculations:

- Average illuminance on a surface
- Illuminance at a point
- Average exitance and average diffuse luminance of a surface
- Exitance and diffuse luminance at a point
- Nondiffuse luminance

These basic quantities are used in a wide range of lighting applications. Computational procedures to determine them are independent of the specific lighting application in which they are used. Some applications, such as sports and roadway lighting, use coordinate systems and light loss factors in ways characteristic to those applications (see Chapter 20, Sports and Recreational Area Lighting, and Chapter 22, Roadway Lighting).

The value in performing these calculations is that they help demonstrate what is and is not important for a lighting design. For example, surface reflectances can significantly affect the lighting power density required to bring the illuminance levels to those required in an indoor space.

2. Identify Luminaire Geometry and Luminous Intensity Distribution. For computational purposes, sources can be categorized by the size and the dimensions they exhibit relative to the distances involved in the computation. It is usual to use the five-times rule to make this determination. This rule states that if the distance between the luminaire and the

computation point is more than five times a luminaire's largest dimension, the luminaire can be treated as a point source. Thus, it is the ratio of luminaire size to computation distance that governs the computational size or geometry category of the luminaire (see the section "Photometry as the Basis for Calculations"). Assuming a luminaire to be a luminous rectangle, the following criteria hold:

- If both of its dimensions are smaller than one-fifth the computation distance, the luminaire is considered a point source.
- If only one dimension is larger than one-fifth the computation distance, the luminaire is considered a line source.
- If both dimensions are larger than one-fifth the computation distance, the luminaire is considered an area source.

Some examples of point, line, and area sources are:

Geometry	Examples
Point	75-W incandescent A lamp in an 8-in.-diameter downlight, used in an office with 8-ft ceilings 1000-W metal halide industrial luminaire with a 24-in. reflector mounted 25 ft above the floor
Line	4-ft unshielded T-12 fluorescent lamp in a small machine shop 6-in. × 4-ft wall-washer luminaire with two T-8 fluorescent lamps
Area	2 × 4-ft troffer with three T-12 fluorescent lamps and a prismatic lens in a classroom with 9-ft ceilings 2 × 2-ft parabolic troffer with two 39-W compact fluorescent lamps, recessed in a 10-ft ceiling and 4 ft from a wall on which luminances are to be calculated 4-in. × 2-ft luminaire with a 20-W T-5 fluorescent lamp and a prismatic lens mounted under a bookshelf over a desk

For computational purposes, luminous intensity distributions are considered either diffuse or nondiffuse. For computational purposes a diffuse luminous intensity distribution (Figure 9-36) is defined as

$$I(\theta, \psi) = I_n \cos \theta$$

where

- I_n = luminous intensity normal ($\hat{n}$) to the luminous surface,
 θ = declination angle measured from the normal,
 ψ = azimuthal angle.

A diffuse luminous intensity distribution does not depend on the azimuthal angle ψ and is axially symmetric about the normal to the luminous surface. It exhibits an intensity that varies only with the cosine of the declination angle θ .

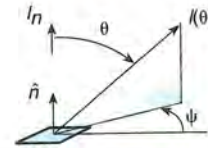


Figure 9-36. Illustration of angles for a diffuse intensity distribution.

If a luminaire has a luminous intensity distribution given by $I(\theta, \psi)$, and if the ratio

$$\frac{I(\theta, \psi)}{I(0^\circ, 0^\circ) \cos \theta}$$

differs from 1.0 by more than 10% for any of the intensities, then the distribution is considered to be nondiffuse. Large errors may result if such a distribution is treated as diffuse. Most luminous intensity distributions exhibited by electric lighting equipment are nondiffuse.

3. Determine the Accuracy and the Complexity

Accuracy. Accuracy requirements are different for different stages in the lighting design process. A preliminary determination of the type of source and required luminaire efficiency can be made, knowing the average illuminance that is required. An accuracy of $\pm 100\%$ is generally sufficient for this determination. Then a preliminary choice of the general type and number of luminaires can be made, knowing the average illuminance that is required. An accuracy of $\pm 25\%$ is generally sufficient for this stage. Illuminance calculations at a point require that both the specific luminous intensity distribution and location of the luminaire(s) be known. Figure 9-37 provides guidance about the required accuracy at different stages of the design process.

Figure 9-37. Expected Accuracy of Lighting Calculations

Available Information	Assumptions Needed to Perform the Calculations	Types of Calculations Possible	Approximate Accuracy
Lamp wattage and efficacy	Luminaire efficiency	Average illuminance	$\pm 100\%$
Lumen output of luminaire	Luminous flux between 0° and 45°	Average illuminance	$\pm 25\%$
Lamp lumens, coefficients of utilization	None	Average illuminance, exitance, or diffuse exitance	$\pm 10\%$
Luminous intensity distribution	None	Illuminance, exitance, or luminance at a point	$\pm 5\%$

The importance of the result and the consequences of uncertainty determine the accuracy required of a calculation. The accuracy, in turn, determines the complexity and cost of the calculation. For purposes of assessing illuminance as it relates to vision- and visibility-related lighting system characteristics, an accuracy of $\pm 25\%$ is probably sufficient. Luminances used for determining the contrast of reading materials should be calculated with an accuracy of $\pm 10\%$. For specification, legal, or comparison purposes, calculations of $\pm 5\%$ accuracy are often desired. A reasonable upper limit to what can be expected from computational accuracy is established by the uncertainty in measurement. Even with high-quality light measurement equipment, $\pm 5\%$ accuracy is usually the best that can be expected. Computational accuracy greater than this cannot be verified by measurement.

Complexity. Calculation complexity is determined by the geometry of the problem. For example, an L-shaped room is computationally more complex than a rectangular room. Similarly, partition shadows and reflections add considerable complexity to the calculations; however, the complex calculations are more accurate.

The need for accuracy is often different for the direct and interreflected components. Although it may be necessary to calculate both the direct and interreflected components, the dominant component should always be calculated with much more accuracy. This, in turn, affects the complexity of the calculation.

4. Identify Required Geometric, Reflectance, and Ancillary Data

Geometric Data. Room dimensions, partition sizes and locations, and surface orientation information such as the slope of a ceiling are necessary geometric information for calculations. Similarly, the luminaire sizes and locations must be determined.

Reflectance Data. Surface reflectances are often unknown at lighting design and calculation time. Unknown reflectances produce an uncertainty that can be determined by calculation. In such cases, those quantities affected by reflectance are calculated twice, using the lowest and highest reasonable values of reflectance that are likely to be present. If these two values lie outside the accuracy requirements listed in Figure 9-37 and below in step 5, then a specification for surface reflectance is required. If the range is small, on the other hand, the reflectances can remain unknown, their values having been found not to significantly affect the lighting system's performance.

Ancillary Data. These data are often specific to a particular application. Examples of such data are BRDFs for visual tasks, r tables for roadway luminance calculations, application adjustment factors (AAFs) for sports lighting, and climate and site data for daylighting calculations. See the application chapters of this handbook for complete information on the ancillary data that might be required for a particular situation.

5. Determine Appropriate Equations. The appropriate equations for average workplane illuminance calculations are determined by the required accuracy. Note that the following equations should also include light loss factors in order to be accurate.

For direct lighting systems with an accuracy of $\pm 100\%$,

$$E_{ave} = \frac{\text{lamp watts} \times \text{efficacy} \times \text{luminaire efficiency} \times \text{number of lamps}}{\text{lighted area}}$$

For indirect lighting systems with an accuracy of $\pm 100\%$,

$$E_{ave} = \frac{\text{lamp watts} \times \text{efficacy} \times \text{luminaire efficiency} \times \text{number of lamps} \times 0.80 \times \text{ceiling reflectance}}{\text{lighted area}}$$

The factor 0.80 above is a reasonable average value in most rooms for what is termed the form factor between the ceiling and floor. That is, for typical rooms, the fraction of luminous flux emitted by the ceiling that reaches the floor is 0.80.

For direct lighting systems and an accuracy of $\pm 25\%$,

$$E_{ave} = \frac{\text{lamp lumens} \times \text{luminaire efficiency} \times \text{number of lamps} \times \text{fraction of luminaire lumens between } 0^\circ \text{ and } 45^\circ}{\text{lighted area}}$$

The amount between 0° and 45° is a reasonable value for the luminaire lumens that reach the floor directly in rooms of typical proportions. There is no equation for indirect lighting systems and an accuracy of $\pm 25\%$.

For both direct and indirect lighting systems and an accuracy of $\pm 10\%$,

$$E_{ave} = \frac{\text{lamp lumens} \times \text{coefficient of utilization} \times \text{number of lamps}}{\text{lighted area}}$$

For an accuracy of $\pm 5\%$, the luminous intensity distribution must be known. The appropriate equations for direct component calculations follow from the geometry of the source, as shown in Figure 9-38.

The appropriate equations for interreflected component calculations are obtained from radiative transfer. The room surfaces are divided into discrete elements and an exitance is calculated for each. More and smaller elements are required for more accurate interreflection calculations.

6. Solve the Equations. Hand calculation is appropriate for small problems with straightforward equations. Spreadsheet programs can often be used. They are the useful option to specialized software, are easy to learn and use, and can be

Figure 9-38. Equations for Direct Component Calculations

Source Geometry	Equation	
	Diffuse distribution	Nondiffuse distribution
Point	Inverse square cosine law	Inverse square cosine law
Line	Configuration factor for a line to a point	Inverse square cosine law, where the line is discretized into pieces that are treated as point sources
Area	Configuration factor for an area to a point	Inverse square cosine law, where the area is discretized into pieces that are treated as point sources

very powerful. More sophisticated computer programs are essential for complex, repetitive, or extended calculations.

COORDINATE SYSTEMS FOR LUMINAIRE PHOTOMETRY

Many lighting calculations involve using luminous intensity distribution data provided by manufacturers in photometric reports. The two basic coordinate systems for luminaire photometry are the spherical coordinate system and the polar coordinate system.

Directions relative to a lamp or luminaire are specified in a spherical coordinate system by angles θ (altitude) and ψ (azimuth). The convention often is used that an azimuth direction along the lamp axis is $\psi = 0^\circ$ or $\psi = 180^\circ$, but when referring to data in a photometric report it is necessary to give careful attention to how the origin of ψ is defined. The terms and symbols used to describe a direction along the lamp axis are

along, parallel, $\parallel$,

and across the lamp axis

across, perpendicular, $\perp$.

A polar plot gives curves that specify the variation with θ of $I(\theta, \psi)$ in an azimuthal plane for stated angles θ . The polar plot is scaled in candelas (cd) measured radially from the photometric center. If the luminous intensity distribution is constant about the vertical axis (as with a round downlight having a vertical lamp orientation), only one curve is given and the angle ψ is not specified. If the luminous intensity distribution is symmetric about both the parallel and perpendicular horizontal axes (as with a horizontally mounted fluorescent lamp), curves may be given only for angles from 0 to 90° . Such a distribution is called quadrilaterally symmet-

ric. In this case, equivalent values of ψ for angles that are between 90° and 360° are calculated as follows:

Range of ψ	Equivalent Angle
90° to 180°	$180^\circ - \psi$
180° to 270°	$\psi - 180^\circ$
270° to 360°	$360^\circ - \psi$

This equivalent angle is the lookup angle used in the table of luminous intensity values.

With less symmetry and increasing optical control complexity, polar plots require more azimuthal planes (and therefore more curves) to adequately define the performance of the luminaire. Sometimes the luminous intensity of a luminaire is required at an angle that is not listed in the photometric report. In such cases interpolation is necessary to obtain accurate results. Linear interpolation is the simplest form of interpolation and is used here, though other more complicated procedures are available.^{3,4}

Figure 9-39 contains a partial luminous intensity table for an imaginary luminaire. Altitude angles are given at 10° intervals, and three azimuth angles are given (0° , 45° , and 90°). To determine the luminous intensity for an azimuth angle of 45° and an altitude angle of, for example, 42.7° , the following procedure can be used.

The fraction equal to the difference between 40° and 42.7° over the difference between 40° and 50° should be calculated:

$$\frac{42.7^\circ - 40^\circ}{50^\circ - 40^\circ} = \frac{2.7^\circ}{10^\circ}$$

From the table, the intensity at 40° is 3012 cd and the intensity at 50° is 3133 cd. The difference between these two values is $3133 - 3012 = 121$ cd, and 27% of this difference is 32.7 cd. This value is then added to the intensity at 40° . Thus the intensity at an altitude of 42.7° and an azimuth of 45° is estimated to be $3012 + 32.7 = 3044.7$, or 3045 cd. A way to check that the interpolated value is correct is that it must lie between the bounding points in the table (3045 cd lies between 3012 and 3133 cd).

Figure 9-39. Partial Example of a Luminous Intensity Distribution

Attitude θ	Intensity (cd) at Azimuth, ψ		
	0°	45°	90°
0°	1866	1866	1866
10°	2019	2653	2304
20°	2431	2721	2512
30°	2512	2964	2581
40°	2639	3012	2744
50°	2818	3133	3008

The examples that follow are taken from actual applications. They are intended to illustrate the general algorithm for lighting calculations discussed above. Only rarely would these examples represent a complete lighting calculation analysis. It is hoped, however, that the preceding discussion and the following examples lead to or augment an understanding of the invisible process of computer calculations. All of the following examples use English units of measurement (such as feet, inches, and footcandles). This is done to help facilitate an understanding of the basic calculations for the audience familiar with this system of units.

Figure 9-40 summarizes the example calculations and their applications. The most useful and most widely applied calculations are those for illuminance, both at a point and averaged over a surface. All illustrations for these examples have been made using a computer drafting system similar to what might be used in many architectural and lighting design firms.

Example 1: Lumen Method for Average Illuminance

The setting for this example is a small open plan office with six workstations formed by partitions. VDTs are used extensively in this space. The office measures 36×30 ft with a 9.5-ft floor-to-ceiling height. The partitions are 5 ft high, and each workstation is 12×12 ft. The layout of the partitions and desks is shown in Figure 9-41a. The section showing the room cavities to be used is in Figure 9-41b.

1. Determine the Quantity to be Calculated. It is decided that an indirect lighting system is used in the space, with the goal of providing a maintained illuminance of 40 fc on the horizontal desk surfaces, which are 2.5 ft above the floor.

Figure 9-40. Example Calculations and Their Applications

Quantity Calculated	Possible Applications	Example*
Average illuminance	Large room with several luminaires and uncertain task locations	1
Illuminance at a point	Localized, known task locations, accent lighting, or evaluation of lighting system uniformity	2 (point) 3 (line) 4 (area)
Average exitance	When interreflections are critical to the illuminance calculations above (exitance is the fundamental quantity for calculating diffuse luminance)	5
Exitance at a point	Calculation of luminance, contrast, or luminance ratios at a point for diffuse surfaces	6
Nondiffuse luminance	Reading materials (signs, print) and glossy surfaces	7

*1: Lumen method for average illuminance in a room with partitions. 2: Parking lot lighting. 3: Lighting a chalkboard in a classroom. 4: Diffuse skylight illuminating a desk. 5: Interreflections from daylight. 6: Luminances produced by a point source for task lighting at a desk. 7: Evaluating contrast produced on printed material.

High-angle light control is needed to suit VDT use in the space. The number of luminaires required to produce this illuminance on the desktops inside the partitioned workstations is the quantity to be calculated.

2. Identify Luminaires and the Information Describing Them. An indirect luminaire is used. The luminaire uses single in-line T-8 fluorescent lamps (lamp lumens = 2900 lm) and is available in continuous lengths that are multiples of 4 ft, up to a maximum length of 24 ft. A 1.5-ft pendant length is recommended by the manufacturer. Photometric data include the CUs that are shown in Figure 9-42.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. The lumen method is used to determine the number of luminaires required, and the following light loss factors are defined: luminaire dirt depreciation factor, lamp lumen depreciation factor, and ballast factor. Other light loss factors are assumed to have a value of 1.0 for this example.

The following calculation strategy is used to take account of the light losses and shadowing produced by the partitions:

- a) An individual partitioned workstation is treated as a small room.

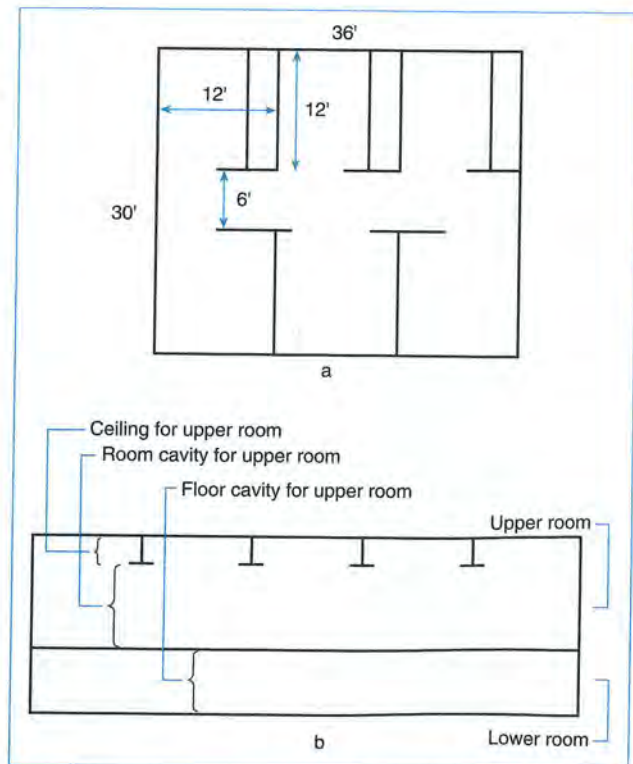


Figure 9-41. Open plan office for example 1: (a) layout, (b) section.

Figure 9-42. Coefficients of Utilization for Indirect Luminaire Used in Example 1

RCR	$\rho_{\text{floor}} = 20$							
	$\rho_{\text{ceiling}} = 80$			70			50	
	$\rho_{\text{wall}} = 70$	50	30	70	50	30	50	30
0	75	75	75	73	73	73	70	70
1	71	69	68	70	68	66	65	64
2	67	64	61	66	63	61	61	59
3	64	59	56	62	58	55	57	54
4	60	55	51	59	54	51	53	50
5	56	50	46	55	50	46	49	45
6	53	47	43	52	46	42	45	42
7	50	43	39	49	43	39	42	38
8	46	39	35	45	39	35	38	35
9	43	36	32	42	36	32	35	31
10	40	33	29	39	33	29	32	28

- b) An imaginary horizontal plane at the level of the top of the partitions represents the ceiling of an individual workstation. The partitions form the walls of this workstation, and the actual working plane is considered as the floor in the calculations. The ceiling reflectance is the effective cavity reflectance of the upper portion of the room, and the floor reflectance is the surface-area-weighted average of the desktop reflectance and effective cavity reflectance of the surfaces below the workplane. In both cases, the effective cavity reflectance is considered from a viewpoint between the workstation ceiling plane and the workplane.
- c) The required illuminance on the desk surface is produced if, taking account of interreflections within the workstation, sufficient light crosses the workstation ceiling plane. This light is directed onto the ceiling plane from the portion of the room above the partitions.
- d) Light crossing the workstation ceiling plane can be characterized both as an exitance from a viewpoint inside the workstation and as an illuminance from a viewpoint above the workstation ceiling plane. It is assumed that the distribution of the light crossing the workstation ceiling plane is diffuse.
- e) For the purpose of lumen calculations within the workstation, the workstation ceiling plane can be considered a perfectly diffuse luminaire. Thus, the coefficients of utilization of a perfectly diffuse emitter can be used.
- f) Working back from the illuminance required on the desk, the luminous output of the diffuse luminaire (that is, the diffuse exitance of the workstation ceiling plane) is calculated.
- g) This exitance is numerically equal to the illuminance that must be produced by the upper part of

the room onto the workstation ceiling plane. That is, the workstation ceiling plane can be considered the floor of the upper part of the room with a required illuminance. It has a reflectance that is the effective cavity reflectance of the partitioned workstation.

- h) The lumen method is applied to the space above the partitions to determine the number of indirect luminaires required to produce this illuminance. Coefficients of utilization for the indirect luminaire are used for this calculation.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The diffuse reflectances of the room surfaces are as follows:

Floor	0.25
Walls	0.60
Ceiling	0.80
Partitions	0.65
Desktops	0.35

It is assumed that the fluorescent lighting system operates continuously through the working day, corresponding to 10 h of operation per start. A maintenance schedule whereby lamps and luminaires are cleaned every year is also assumed.

The luminaire dirt depreciation light loss factor is determined following the procedure given in Figure 9-14. Since the luminaire has an opaque bottom surface and no top enclosure, it is in maintenance category VI. Using the method given in Figure 9-15, the operating atmosphere must be classified, and for this situation is determined to be clean. The luminaire dirt depreciation light loss factor is then determined from Figure 9-17, and the depreciation curve for luminaires operating in a clean atmosphere. For a yearly maintenance cycle, the luminaire dirt depreciation factor is determined to be 0.85.

A more accurate determination can be made by referring to manufacturer's data for the specific lamp type to be used. Allowance can be made for the assumption that the lamps are operated for 10 h per start. The data in Chapter 6 are based on 3 h per start; thus it is assumed that the lamp lumen depreciation factor should be slightly adjusted to 0.88.

The ballast factor for the magnetic ballasts used in this luminaire is 0.95. The total light loss factor (LLF) is thus $LLF = 0.85 \times 0.88 \times 0.95 = 0.711$.

5. Determine Appropriate Equations. From Equation 9-50, the lumen method equation for determining the required number of luminaires is

$$\text{number of luminaires} = \frac{E_{\text{maintained}} \times \text{workplane area}}{\text{lamps per luminaire} \times \text{lamp lumens} \times \text{CU} \times \text{LLF}}$$

6. Solve the Equations. The lumen method is applied first to a workstation. The CU is determined from the room cavity ratio (RCR) and the surface reflectances (determined as shown in the section "Average Illuminance Calculation: The Lumen Method"):

$$\text{RCR} = \frac{5h(l+w)}{l \times w}$$

where h is the cavity height, l is the cavity length, and w is the cavity width. Because the ceiling of a workstation is at the level of the top of the partitions and the floor is at workplane level, the cavity height is $5 - 2.5 = 2.5$ ft. This value and the workstation dimensions give

$$\text{RCR} = \frac{5 \times 2.5 \times (12 + 12)}{12 \times 12} = 2.08$$

Below the workplane level is a floor cavity, for which the effective cavity reflectance must be determined. It has a base reflectance of 0.25 (the actual floor) and a wall reflectance of 0.60, and the floor cavity ratio (FCR) is given by

$$\text{FCR} = \frac{5 \times 2.5 \times (12 + 12)}{12 \times 12} = 2.08$$

Figure 9-27 is read to determine the effective floor cavity reflectance (ρ_{FC}), using the floor cavity ratio 2.08 and the reflectances 0.25 and 0.60. By linear interpolation, the result is $\rho_{FC} = 0.23$.

In an area as small as the workstation, the size of the desk is significant. A surface-area-weighted average reflectance (ρ_{FCave}) can be determined for the floor or base of the cavity as shown in Equation 9-58. For the present case,

$$\rho_{FCave} = \frac{A_{FC} \rho_{FC} + A_{DT} \rho_{DT}}{A_{FC} + A_{DT}}$$

where the subscript DT indicates the desktop. A_{FC} and A_{DT} indicate the areas of the floor and desktop, respectively. If the area of the desktop is 18 ft^2 , the effective floor cavity reflectance is

$$\rho_{FCave} = \frac{(12 \times 12 - 18) \times 0.23 + 18 \times 0.35}{(12 \times 12 - 18) + 18} = 0.245$$

The reflectance assigned to the workstation ceiling plane is the effective cavity reflectance of the upper portion of the room from a viewpoint inside the workstation. Because the room height is 9.5 ft and the partitions are 5 ft tall, the cavity height is 4.5 ft. The ceiling cavity ratio (CCR) is given by

$$\text{CCR} = \frac{5 \times 4.5 \times (36 + 30)}{36 \times 30} = 1.37$$

The base reflectance of this cavity is the ceiling reflectance of the room, 0.80, and the wall reflectance is the wall reflectance of the room, 0.60. Referring to Figure 9-27, the effective ceiling cavity reflectance for the workspace is 0.65.

Thus, the parameters for determining the CU in the workstation are $\text{RCR} = 2.08$, $\rho_{\text{ceiling}} = 0.65$, $\rho_{\text{walls}} = 0.60$, and $\rho_{FCave} = 0.245$. A CU table for a perfectly diffuse emitter is given in Figure 9-30. Linear interpolation gives the value $\text{CU} = 0.80$.

As stated in the CU table, all values assume a floor cavity reflectance of 0.20. Thus in this situation the CU value must be modified to take account of the high floor cavity reflectance. The multiplier for this purpose is interpolated from the table of multipliers in Figure 9-29. For $\rho_{FCave} = 0.245$, the result is multiplier = 1.06, and so $\text{CU} = 0.80 \times 1.06 = 0.85$.

From the lumen method equation, the number of lumens required to pass through the workstation ceiling plane is

lumens required =

$$\frac{E_{\text{maintained}} \times \text{workplane area}}{\text{CU}} = \frac{(40 \times 12 \times 12)}{0.85} = 6776 \text{ lm}$$

The illuminance that must be produced on this plane is thus

$$E_{\text{required}} = \frac{\text{required lumens}}{\text{area of workstation}} = \frac{6776}{(12 \times 12)} = 47 \text{ fc}$$

The lumen method is now applied to the upper portion of the room. The room cavity height is the distance between the partition tops and suspended luminaires, 3 ft. The RCR is

$$\text{RCR} = \frac{5 \times 3 \times (36 + 30)}{36 \times 30} = 0.916$$

Since the luminaires are suspended, an effective ceiling cavity reflectance must be determined. The CCR is

$$\text{CCR} = \frac{5 \times 1.5 \times (36 + 30)}{36 \times 30} = 0.458$$

The base reflectance of this cavity is the room ceiling reflectance, 0.80, and the wall reflectance is the room wall reflectance, 0.60. Referring to Figure 9-27, the effective ceiling cavity reflectance is $\rho_{CC} = 0.74$.

The effective floor reflectance of the room is determined from the data on the workstations. The effective reflectance of the workplane has been calculated to be 0.245, and this plane forms the cavity base. The partitions, having a reflectance of 0.65, form the cavity walls. The cavity height is the height between the workplane and the workstation ceiling plane, 2.5 ft. The cavity ratio is

$$CR = \frac{5 \times 25 \times (12 + 12)}{12 \times 12} = 2.08$$

Referring again to Figure 9-27, the effective floor cavity reflectance is $\rho_{FC} = 0.24$.

Thus, the parameters for determining the CU are $RCR = 0.916$, $\rho_{CC} = 0.74$, $\rho_{walls} = 0.60$, and $\rho_{FC} = 0.24$. Interpolation in the CU table for the indirect luminaire (Figure 9-42) gives $CU = 0.67$. As previously, a multiplier must be determined to correct for the difference between the assumed floor reflectance of 0.20 and the value 0.24. From Figure 9-29, the result is Multiplier = 1.08. Thus the corrected coefficient of utilization is $CU = 0.67 \times 1.08 = 0.72$.

The other parameters for the lumen method equation are lamps per luminaire = 1 and lamp lumens = 2900 lm.

Finally, the number of luminaires is

number of luminaires

$$\begin{aligned} &= \frac{E_{\text{maintained}} \times \text{workplane area}}{\text{lamps per luminaire} \times \text{lamp lumens} \times CU \times LLF} \\ &= \frac{47 \times 36 \times 30}{1 \times 2900 \times 0.72 \times 0.771} = 31.5 \end{aligned}$$

An architecturally practical layout of these luminaires would involve 32 luminaires. One such arrangement is four rows, each 32 ft long, consisting of eight luminaires per row.

Example 2: Lighting a Small Parking Area

The setting for this example is a small parking lot near an office building. The parking lot measures 100×100 ft and is adjacent to a three-story office building. It is desired to keep the equipment height consistent with the architectural scale of the building. An analysis is to be performed to see if a single luminaire on a pole can sufficiently illuminate the entire parking lot. The pole is placed at the center of the area.

1. Determine the Quantity to be Calculated. A diagram of the parking area and the proposed lighting system appears in Figure 9-43. To evaluate the effectiveness of a single pole location, the illuminances are calculated at the points of a 5×5 -ft rectangular grid on the pavement surface. This analysis is performed with three typical pole heights: 15, 20, and 25 ft. The evaluation criterion is the illuminance recommendation (see Chapter 22, Roadway Lighting) for a low-activity-level, open parking facility: a minimum horizontal illuminance of 0.2 fc, minimum vertical illuminance of 0.1 fc, and a uniformity criterion that the ratio of maximum to minimum illuminance is to be no greater than 20:1.

2. Identify Luminaires and the Information Describing Them. The luminaire to be used in the analysis is Type VS with a square distribution, using a 250-W clear metal halide lamp, and having a lumen rating of 20,500 lm. Photometric data are available and are shown in Figure 9-44 as they might appear in a photometric report.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. Initial calculations are performed at the points along the diagonal of this grid. It is anticipated that

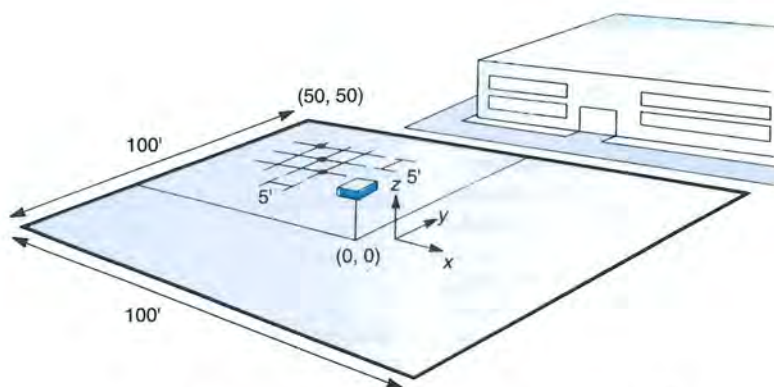


Figure 9-43. Diagram of parking area for Example 2.

Figure 9-44. Parking Lot Luminaire Luminous Intensity Distribution for Type A Photometry*

Vertical Angle	Intensity (cd) at Lateral Angle										
	0°	5°	15°	25°	35°	45°	55°	65°	75°	85°	90°
0.0°	2886	2886	2886	2886	2886	2886	2886	2886	2886	2886	2886
2.5°	2879	2887	2887	2904	2921	2929	2946	2954	2954	2954	2963
5.0°	2846	2854	2879	2904	2921	2938	2946	2963	2963	2963	2963
7.5°	2829	2829	2862	2879	2896	2896	2904	2912	2921	2929	2929
10.0°	2779	2795	2812	2820	2829	2837	2854	2854	2879	2871	2879
12.5°	2745	2745	2762	2779	2779	2795	2812	2837	2846	2854	2846
15.0°	2678	2678	2695	2728	2753	2762	2787	2812	2820	2812	2812
17.5°	2628	2628	2645	2678	2712	2737	2770	2795	2812	2795	2787
20.0°	2578	2578	2603	2636	2670	2712	2779	2837	2854	2829	2804
22.5°	2561	2553	2553	2611	2653	2728	2812	2904	2921	2837	2804
25.0°	2544	2553	2544	2628	2703	2753	2804	2879	2879	2804	2762
27.5°	2461	2477	2511	2620	2720	2770	2829	2896	2887	2804	2770
30.0°	2427	2435	2461	2611	2720	2812	2904	3021	2963	2829	2812
32.5°	2578	2569	2494	2728	2779	2904	3046	3155	3021	2871	2837
35.0°	2712	2678	2561	2929	2896	3080	3297	3356	3138	3046	2996
37.5°	3046	2921	2653	3122	3063	3406	3599	3691	3373	3306	3339
40.0°	3565	3331	2912	3456	3389	4051	3967	4268	3590	3490	3565
42.5°	3733	3456	3122	3892	3825	4695	4293	4670	3749	3574	3724
45.0°	4118	3599	3189	4067	4101	5030	4729	4812	3984	3833	4109
47.5°	4185	3841	3297	4469	4377	5097	4896	5214	4101	3833	4327
50.0°	3749	3565	3482	4570	4494	5038	4871	5381	4101	3691	4293
52.5°	3314	3097	3465	4327	4243	4829	4645	5281	4385	3716	4770
55.0°	3046	3097	3758	3992	4093	5088	4888	5842	5139	4067	5164
57.5°	2142	2544	3130	4084	5088	6955	5716	5591	4553	3825	4151
60.0°	1741	2134	2410	3281	4461	5323	4385	4143	3808	3197	3448
62.5°	1490	1942	2260	2820	4076	4235	3716	3348	3908	3021	3557
65.0°	1205	1657	2402	2293	3724	3515	3540	3389	3858	3180	4235
67.5°	1038	1398	2193	2151	3574	4009	4452	3816	4921	3222	4143
70.0°	836	1105	1774	1967	3565	4645	5189	4093	4720	3339	3532
72.5°	619	795	1205	1758	2753	3657	4185	3607	3549	2059	2360
75.0°	418	460	518	1138	2025	3021	3063	1891	2092	1013	1364
77.5°	234	192	200	309	535	1029	1071	594	493	326	251
80.0°	117	100	108	142	175	184	209	167	108	92	100
82.5°	50	58	50	50	58	66	50	50	41	33	41
85.0°	33	16	41	16	25	16	16	16	16	16	16
87.5°	0	0	0	0	0	0	0	0	0	0	0
90.0°	0	0	0	0	0	0	0	0	0	0	0

*Total lumen output is 20,500 lm.

the illuminance is likely to be lowest at the corners of the parking area because the distance from the luminaires is greatest at the corners.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The necessary dimensions are shown in Figure 9-43. On their photometric reports, manufacturers often recommend a total light loss factor to be used with their luminaires. In this case, the manufacturer recommended a total light loss factor of 0.85. Reflectances are unimportant, since this is an outdoor application.

5. Determine Appropriate Equations. The smallest mounting height to be used is 15 ft, which is more than 5 times the largest dimension of the luminaire. Thus, the five-times rule is satisfied for any point on the calculation grid,

and the luminaire can be treated as a point source. The inverse square cosine law can be used for illuminance computations:

$$E = \frac{I(\theta, \psi) \cos \theta}{D^2}$$

The geometry of this problem allows each of the trigonometric and distance quantities in this equation to be expressed in rectangular coordinates (Figure 9-43):

$$\theta = \arctan \left(\frac{\sqrt{x^2 + y^2}}{z} \right)$$

$$\psi = \arctan \left(\frac{x}{y} \right)$$

$$\cos \xi = \frac{z}{\sqrt{x^2 + y^2 + z^2}}$$

$$D^2 = x^2 + y^2 + z^2$$

These combine to give the following expression for the horizontal and vertical illuminances, E_H and E_V , respectively:

$$E_H = I(\theta, \psi) \frac{z}{(x^2 + y^2 + z^2) \sqrt{x^2 + y^2 + z^2}}$$

$$E_V = I(\theta, \psi) \frac{y}{(x^2 + y^2 + z^2) \sqrt{x^2 + y^2 + z^2}}$$

6. Solve the Equations. An analysis is performed at the grid points along a diagonal. Referring to Figure 9-43, the rectangular coordinates can be determined with respect to the luminaire. Three values of z are used for each pair of x and y coordinates, each value of z representing one of the three pole heights to be evaluated. The point ($x = 0, y = 0$) is directly underneath the luminaire. The point ($x = 50, y = 50$) is at the corner of the parking lot. The luminous intensity values are obtained by linear interpolation from Figure 9-44.

The intensity at ($\theta = 43.3^\circ, \psi = 45.0^\circ$) is estimated as 3801 cd. The results of all intermediate calculations are summarized in Figure 9-45. The horizontal and vertical illuminance at each position is calculated for each of the three pole heights.

At a distance of 50 ft, the horizontal illuminance near the corner of the lot is below 0.2 fc for a pole height of 15 or 20 ft. Only for a pole height of 25 ft is the minimum illuminance requirement of 0.2 fc met over the entire parking lot. This pole height also minimizes the maximum-to-minimum illuminance ratio over the parking area, which meets the required maximum ratio of 20:1 from Chapter 22, Roadway Lighting, as demonstrated below. Additionally, the 25-ft pole height produced a minimum vertical illuminance of 0.26 fc, which meets the minimum requirement.

The maximum-to-minimum ratio for the pole height of 25 ft is calculated as follows:

$$\frac{\text{maximum illuminance}}{\text{minimum illuminance}} = \frac{4.54 \text{ fc}}{0.23 \text{ fc}} = \frac{19.7}{1}$$

Thus the ratio is 19.7:1, which meets IESNA recommendations for uniformity.

Example 3: Calculation of Illuminance at a Point: Direct and Interreflected Components

This example concerns lighting a chalkboard.

1. Determine the Quantity to Be Calculated. The quantity of interest is the illuminance at a point on a chalkboard.

Figure 9-45. Intermediate Calculations for Example 2

x (ft)	y (ft)	z (ft)	θ	ψ	I (cd)	D (ft)	E (fc)
0.0	0.0	15.0	0.0°	0.0°	2885	15.0	12.83
0.0	0.0	20.0	0.0°	0.0°	2886	20.0	7.22
0.0	0.0	25.0	0.0°	0.0°	2886	25.0	4.62
5.0	5.0	15.0	25.2°	45.0°	2754	16.6	9.03
5.0	5.0	20.0	19.5°	45.0°	2717	21.2	5.70
5.0	5.0	25.0	15.8°	45.0°	2754	26.0	3.92
10.0	10.0	15.0	43.3°	45.0°	4802	20.6	8.23
10.0	10.0	20.0	35.3°	45.0°	3119	24.5	4.24
10.0	10.0	25.0	29.5°	45.0°	2804	28.7	2.96
15.0	15.0	15.0	54.7°	45.0°	5057	26.0	4.32
15.0	15.0	20.0	46.7°	45.0°	5076	29.2	4.08
15.0	15.0	25.0	40.3°	45.0°	4128	32.8	2.92
20.0	20.0	15.0	62.1°	45.0°	4409	32.0	2.02
20.0	20.0	20.0	54.7°	45.0°	5057	34.6	2.44
20.0	20.0	25.0	48.5°	45.0°	5073	37.7	2.37
25.0	25.0	15.0	67.0°	45.0°	3910	38.4	1.04
25.0	25.0	20.0	60.5°	45.0°	5105	40.6	1.53
25.0	25.0	25.0	54.7°	45.0°	5057	43.3	1.56
30.0	30.0	15.0	70.5°	45.0°	4147	45.0	0.68
30.0	30.0	20.0	64.8°	45.0°	3573	46.9	0.69
30.0	30.0	25.0	59.5°	45.0°	5649	49.2	1.19
35.0	35.0	15.0	73.1°	45.0°	3504	51.7	0.38
35.0	35.0	20.0	68.0°	45.0°	4136	53.4	0.54
35.0	35.0	25.0	63.2°	45.0°	4437	55.5	0.65
40.0	40.0	15.0	75.1°	45.0°	2941	58.5	0.22
40.0	40.0	20.0	70.5°	45.0°	4147	60.0	0.38
40.0	40.0	25.0	66.2°	45.0°	3752	61.8	0.40
45.0	45.0	15.0	76.7°	45.0°	1666	65.4	0.09
45.0	45.0	20.0	72.6°	45.0°	3632	66.7	0.24
45.0	45.0	25.0	68.6°	45.0°	4289	68.4	0.34
50.0	50.0	15.0	78.0°	45.0°	860	72.3	0.03
50.0	50.0	20.0	74.2°	45.0°	3225	73.5	0.16
50.0	50.0	25.0	70.5°	45.0°	4147	75.0	0.25

This is used to determine if a design illuminance criterion of 20 fc on the chalkboard is met. It is assumed that the point at the center of the chalkboard is representative; this point is used for calculations. The layout is shown in Figures 9-46 and 9-47.

2. Identify Luminaires and the Information Describing Them. A pair of 1 × 4-ft recessed troffers, each with two T-12 fluorescent lamps, are used. The total produced by a sin-

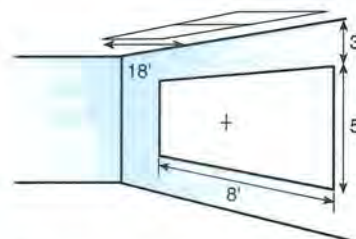


Figure 9-46. Pertinent room dimensions for Example 3, lighting a chalkboard.

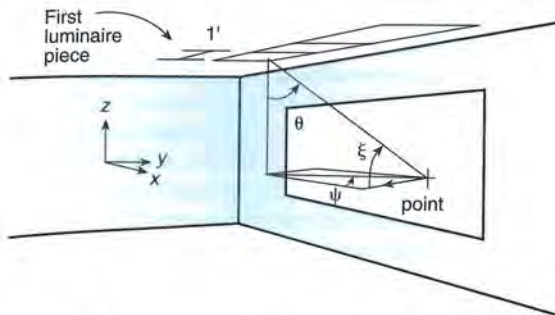


Figure 9-47. Illustration of angles and dimensions for Example 3.

gle luminaire is 3791 lm. The luminous intensity distribution for this luminaire is shown in Figure 9-48 as it might appear in a photometric report.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. The direct component of illuminance is calculated from the two luminaires. It is not possible to treat the luminaires as point sources because of their size and proximity to the chalkboard. Because of their shape, they are considered to be line sources. Therefore the five-times rule is used to determine the number of discrete pieces of luminaire that must be considered.

The distance D from the center of one of the luminaires to the center of the chalkboard, as can be seen in Figures 9-46 and 9-47, is

$$D = \sqrt{x^2 + y^2 + z^2} = \sqrt{2^2 + 1.5^2 + 5.5^2} = 6.04 \text{ ft}$$

The five-times rule requires the dimensions of the discrete pieces of the luminaire to be no greater than $\frac{6.04}{5} = 1.2$ ft. Since the luminaires measure approximately 1×4 ft, each can be discretized into four sections of 1 ft² along its length. Each discrete piece of the luminaire is assumed to emit 25%

Figure 9-48. Luminous Intensity Distribution for Schoolroom Luminaire

Angle θ	Intensity (cd)		
	Along ($\psi = 0^\circ$)	$\psi = 45^\circ$	Across ($\psi = 90^\circ$)
0°	1531	1531	1531
5°	1440	1554	1547
15°	1357	1495	1523
25°	1238	1401	1519
35°	1072	1331	1652
45°	852	1242	1259
55°	586	771	612
65°	155	205	216
75°	26	31	26
85°	4	13	9
90°	0	0	0

of the luminaire lumens. Therefore, each has a luminous intensity distribution equal to 25% that of the entire luminaire.

The interreflected component is determined using the average interreflected illuminance over the chalkboard, since the average interreflected illuminance variation is likely to be small. It is assumed that the principal interreflection is between the chalkboard and a section of the ceiling nearby. The floor is very likely to have a low reflectance and is ignored for purposes of interreflected component calculations. Other walls are assumed to be sufficiently far from the chalkboard to give a negligible contribution to the interreflected component. Note that luminaires in the room other than those used to directly light the chalkboard may also produce direct and interreflected illuminance on the chalkboard. Other sources of illumination are not considered in this example.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The chalkboard reflectance ρ_1 is 0.25. The ceiling reflectance ρ_2 is 0.80. The pertinent room dimensions are as shown in Figure 9-46.

5. Determine Appropriate Equations

Direct Component. The discrete luminaire pieces are small enough for the inverse square cosine law to be applied for each of the eight pieces (two four-foot luminaires, each divided into one-foot sections), and the illuminances (calculated using Equation 9-4) added together to give the total illuminance:

$$E = \sum_{i=1}^8 \frac{I_i \cos \xi_i}{D_i^2}$$

where

I_i = intensity of the i th piece in the direction to the center of the chalkboard,

ξ_i = angle between the normal to the chalkboard surface and a line from the i th piece to the center of the chalkboard,

D_i = distance between the center of the chalkboard and the i th piece.

Interreflected Component. A general equation for interreflected illuminance between two diffuse surfaces is used, based on Equation 9-23a:

$$\bar{E}_{1 \text{ inter}} = \frac{\bar{E}_{1 \text{ dir}} + \bar{E}_{2 \text{ dir}} f_{1 \rightarrow 2}}{1 - \rho_1 \rho_2 f_{1 \rightarrow 2} f_{2 \rightarrow 1}} - \bar{E}_{1 \text{ dir}}$$

where

$\bar{E}_{1 \text{ dir}}$ = direct illuminance onto surface 1,

$\bar{E}_{2 \text{ dir}}$ = direct illuminance onto surface 2,

$f_{1 \rightarrow 2}$ = radiative exchange form factor from surface 1 to surface 2,

$f_{2 \rightarrow 1}$ = radiative exchange form factor from surface 2 to surface 1,

ρ_1, ρ_2 = diffuse reflectances of surfaces 1 and 2.

In the present application, surface 1 is the chalkboard and surface 2 is the ceiling near the chalkboard. In this case only the chalkboard has an initial illuminance, and the general equation becomes

$$\bar{E}_{\text{inter}} = \frac{\bar{E}_{\text{dir}}}{1 - \rho_{cb}\rho_c f_{cb \rightarrow c} f_{c \rightarrow cb}} - \bar{E}_{\text{dir}}$$

where

- $\bar{E}_{\text{dir}}$ = direct illuminance on the chalkboard,
- $f_{cb \rightarrow c}$ = radiative exchange form factor between the chalkboard (cb) and the ceiling (c)
- $f_{c \rightarrow cb}$ = radiative exchange form factor between the ceiling and the chalkboard,
- ρ_{cb}, ρ_c = diffuse reflectances of the chalkboard and ceiling.

6. Solve the Equations

Direct Component. The intermediate quantities required to calculate the direct component of illuminance are shown below and in Figure 9-49:

$$\begin{aligned} D_i &= \sqrt{x_i^2 + y_i^2 + z_i^2} \\ \theta_i &= \arccos\left(\frac{z_i}{D_i}\right) \\ \psi_i &= \arctan\left(\frac{y_i}{x_i}\right) \\ \cos \xi &= \frac{y_i}{D_i} \end{aligned}$$

The angle ψ is measured from the lamp axis of the luminaire. The plane of data corresponding to a value of zero for this angle is identified as "along" in Figure 9-48. Intensities for angles not between 0 and 90° are obtained as discussed above. Negative angles can be converted to positive angles by adding 360°. The luminous intensities are linearly interpolated from the luminous intensity distribution data in Figure 9-48 and divided by 4 because of the discretization of each luminaire into four pieces. All of the calculated values for each of the eight luminaire pieces are shown in Figure 9-49. The total direct illuminance is then the sum of the partial illuminances in the column at the far right of the table, or 18.5 fc.

Figure 9-49. Intermediate Calculations for Example 3

Luminaire Piece (i)	x_i	y_i	z_i	D_i	$\cos \xi_i$	θ_i	ψ_i	I_i	E_i
1	-3.5	1.5	5.5	6.69	0.224	34.7°	-23.2°	302	1.51
2	-2.5	1.5	5.5	6.22	0.241	27.8°	-31.0°	331	2.06
3	-1.5	1.5	5.5	5.89	0.255	21.0°	-45.0°	360	2.65
4	-0.5	1.5	5.5	5.72	0.262	15.9°	-71.6°	377	3.02
5	0.5	1.5	5.5	5.72	0.262	15.9°	71.6°	377	3.02
6	1.5	1.5	5.5	5.89	0.255	21.0°	45.0°	360	2.65
7	2.5	1.5	5.5	6.22	0.241	27.8°	31.0°	331	2.06
8	3.5	1.5	5.5	6.69	0.224	34.7°	23.2°	302	1.51

Interreflected Component. As shown above, this calculation requires the initial average illuminance on the chalkboard. For the purpose of calculating the interreflected component, it is assumed to be the same as the average illuminance on the entire wall. This average illuminance can be calculated from (luminaire lumens incident onto the chalkboard)/(area of the chalkboard wall). The luminaires have intensity distributions that are symmetric both along and across the lamp axis and are mounted close to the chalkboard wall. Thus it can be assumed that approximately 50% of the luminaire lumens reach this surface directly. For each luminaire, 50% of 3791, or 1895.5 lm, reaches the chalkboard wall directly. Because there are two luminaires, the total flux incident on the chalkboard wall is assumed to be 3791 lm. The area of the chalkboard wall is 64 ft² (8 × 8 ft). Therefore,

$$\bar{E}_{\text{dir}} = \frac{\text{incident flux}}{\text{area}} = \frac{3791 \text{ lm}}{64 \text{ ft}^2} = 59 \text{ fc}$$

Solving for the interreflected illuminance component gives

$$\bar{E}_{\text{inter}} = \frac{\bar{E}_{\text{dir}}}{1 - \rho_{cb}\rho_c f_{cb \rightarrow c} f_{c \rightarrow cb}} - \bar{E}_{\text{dir}}$$

where $\bar{E}_{\text{dir}}$, ρ_{cb} , and ρ_c have been previously defined, and $f_{cb \rightarrow c}$ and $f_{c \rightarrow cb}$ are both assumed to equal 0.2. Hence $\bar{E}_{\text{inter}} = 0.5 \text{ fc}$. The total illuminance at the point is then $E = \bar{E}_{\text{dir}} + \bar{E}_{\text{inter}} = 18.5 \text{ fc} + 0.5 \text{ fc} = 19 \text{ fc}$.

Given the accuracy of the equations used (which is no better than 5%, as discussed in the description of the algorithm above), the calculated illuminance of 19 fc may or may not meet the established design criterion of 20 fc. Further analysis on the part of the designer is probably necessary in this borderline case.

Note that the interreflected component is significantly smaller than the direct component. Because of this, a more elaborate calculation of the interreflected component produced by these luminaires is not required.

Example 4: Calculation of Illuminance at a Point from an Area Source: Direct Component Only

This example addresses skylights in a small classroom in Denver, Colorado.

1. Determine the Quantity to Be Calculated. The quantity of interest is the direct component of illuminance at a point on a desk in a small classroom. The calculation point is at the center of the room on a desk 2.5 ft high. The room is 28 × 28 ft with a floor-to-ceiling height of 10 ft. It has a ceiling reflectance of 0.80, a wall reflectance of 0.46, and a floor reflectance of 0.20.

2. Identify Sources and the Information Describing Them. The room is lighted by an array of four domed sky-

lights, as shown in Figure 9-50. Each skylight is made of plastic that exhibits a diffuse transmittance of 0.15 for light incident perpendicular to the surface. For light incident at other angles, the transmittance is diffuse but the value is reduced. This diffuse directional transmittance is given by the equation $T(\theta) = 0.15 \cos^2 \theta$, where θ is the angle of incidence. This equation is used for the direct solar contribution. The total diffuse transmittance T for light incident equally from all directions is 0.10.

3. Determine the Accuracy and Complexity. The direct component is calculated from the skylights, assuming that they are diffuse area sources. The equation for the illuminance produced by a diffuse area source is used (Equation 9-9). This equation requires the source exitance, which in this case is the skylight exitance. This exitance is produced by

sunlight and sky light transmitted through the dome of the skylight.

Since the skylight is domed, the transmittance is almost independent of the direction from which the light arrives onto the skylight. This would not be true if the skylight were flat. Domed skylights exhibit a transmittance change due to the thinning of material at the top of the dome. The effect of domed skylights is determined by evaluating the change in transmittance.

The illuminance produced by the skylights is a function of their exitance, which in turn is a function of the daylight illuminance on them and their transmittance. Both of these quantities are affected by the sun's position. Thus the calculation must be made for a specific date, time, and sky condition as described in Chapter 8, Daylighting.

The calculation for the interreflected component is shown in example 5.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The date and time of the example calculation is April 10, 12 noon for Denver, Colorado. The sky condition is assumed to be clear. The available horizontal illuminance, as calculated according to the method described in Chapter 8, Daylighting, is $E_{\text{sun}} = 9150$ fc and $E_{\text{sky}} = 1400$ fc. The solar altitude for these conditions is 57.5° , so the sun is 32.5° from the zenith.

5. Determine Appropriate Equations. The equation for the illuminance produced by a diffuse area source is $E = Mc$, where M is the diffuse exitance of the source and c is the configuration factor for the area to the point. In this case the configuration factor is for a rectangle to a point in a plane parallel to the plane of the rectangle. The general equation, from Figure 9-3, is:

$$c = \frac{1}{2\pi} \sum_{i=1}^2 \sum_{j=1}^2 F(x_i, y_j) (-1)^{i+j}$$

where

$$F(x_i, y_j) = \frac{x_i}{\sqrt{x_i^2 + z^2}} \arctan \left(\frac{y_j}{\sqrt{x_i^2 + z^2}} \right) + \frac{y_j}{\sqrt{y_j^2 + z^2}} \arctan \left(\frac{x_i}{\sqrt{y_j^2 + z^2}} \right)$$

x_i = distance from the calculation point to the i th edge of the rectangular source in the x direction,

y_j = distance from the calculation point to the j th edge of the rectangular source in the y direction,

z = distance between the plane containing the calculation point and the plane of the source.

Since there is more than one diffuse area source, the total direct component of illuminance is

$$E = \sum_{i=1}^4 M_i c_i$$

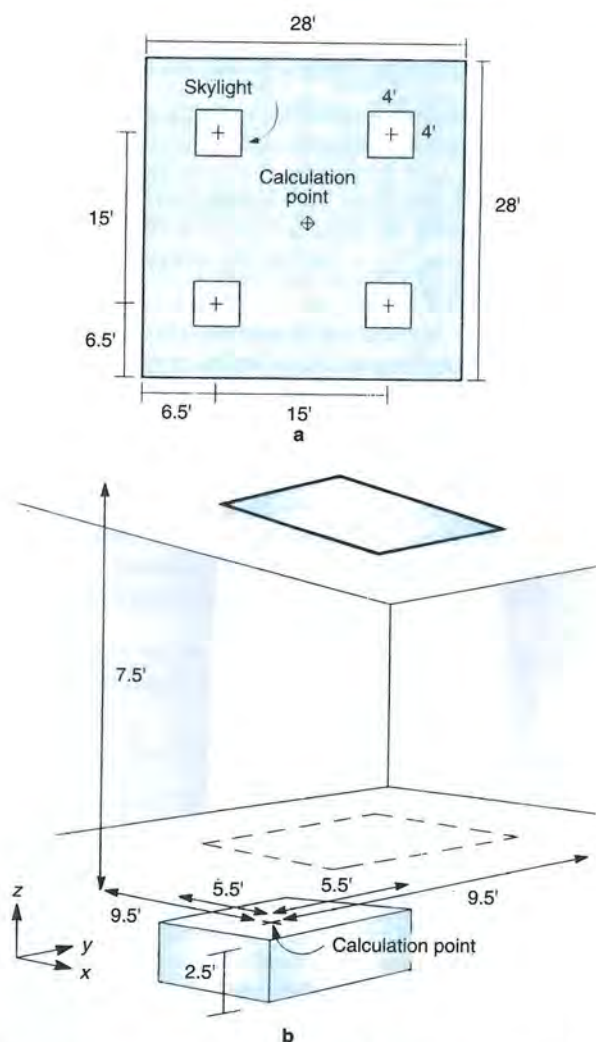


Figure 9-50. Classroom and skylights for Examples 4 and 5: (a) plan, (b) perspective.

All four skylights have the same transmittance characteristics, and their proximity means that they have the same sky and sun illuminance. Thus they exhibit the same exitance. This gives

$$E = M \sum_{i=1}^4 c_i$$

In the present example, the calculation point is at the center of the room and is thus symmetrically placed with respect to the skylights, and the four configuration factors are the same. The illuminance is then $E = 4Mc$.

The exitance M of the skylight within the room is

$$M = E_{\text{sun}} T_{\text{net}} + E_{\text{sky}} T$$

where

E_{sun} = horizontal illuminance produced by the sun,
 E_{sky} = horizontal illuminance produced by the sky,
 T_{net} = net directional transmittance of the skylight,
 T = total diffuse transmittance of the skylight.

The equation for the net directional transmittance T_{net} of a domed skylight for directional light (i.e., from the sun) is $T_{\text{net}} = 1.25 T(0) [1.18 - 0.416T(0)]$, where $T(0)$ is the diffuse transmittance for light incident perpendicularly to the surface of the plastic (see Chapter 8, Daylighting).

6. Solve the Equations. The skylight net transmittance is $T_{\text{net}} = 1.25(0.15)[1.18 - 0.416(0.15)] = 0.210$. The skylight exitance M is $M = (9150)(0.210) + (1400)(0.10) = 2057 \text{ lm/ft}^2$.

The configuration factor from one of the skylights to the point is calculated from the equation shown above in step 5. The distances involved are $x_1 = 5 \text{ ft}$, $x_2 = 9.5 \text{ ft}$, $y_1 = 5.5 \text{ ft}$, $y_2 = 9.5 \text{ ft}$, and $z = 7.5 \text{ ft}$. The resulting configuration factor c is 0.0104.

The illuminance at the calculation point from the four skylights is $E = 4Mc = 4(2057)(0.0104) = 85.5 \text{ fc}$. Thus, for a clear sky condition at 12 noon on April 10 in Denver, the four skylights produce a direct illuminance of 86 fc on the desk in the middle of the room.

Example 5: Calculation of Illuminance at a Point from an Area Source: Interreflected Component

This example also addresses skylights in a small classroom in Denver, Colorado.

1. Determine the Quantity to Be Calculated. The quantity of interest is the interreflected component of illuminance at a point on a desk in a small classroom. The direct illuminance component has been calculated in Example 4 and is 86 fc. The calculation point is the same as for Example 4: at the center of the room, on a desk 2.5 ft above the floor. The room is $28 \times 28 \text{ ft}$ with a floor-to-ceiling height of 10

ft. It has a ceiling reflectance of 0.80, a wall reflectance of 0.46, and a floor reflectance of 0.20.

2. Identify Sources and the Information Describing Them. The room is lighted by an array of four domed skylights, as shown in Figure 9-50. The skylights are described in Example 4.

3. Determine the Accuracy and Complexity. The interreflected component due to the skylights is calculated assuming that they are diffuse area sources. The interreflections in the room are likely to produce uniform room surface exitances, so a simple three-surface radiative transfer model is used. That is, the ceiling and floor are each treated as separate surfaces, and the four walls are grouped together and treated as the third surface. Calculating the interreflection of light results in a single final exitance for the floor, walls, and ceiling.

The ceiling and walls are then treated as diffuse area sources, and the illuminance they produce at the calculation point is the interreflected component. The equation for the illuminance produced by a diffuse area source is used.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The date and time of the example calculation is April 10, 12 noon for Denver, Colorado. The sky condition is assumed to be clear. The available horizontal illuminance, calculated as described in Chapter 8, Daylighting, is $E_{\text{sun}} = 9150 \text{ fc}$ and $E_{\text{sky}} = 1400 \text{ fc}$. The reflectance data are described above in step 1.

5. Determine Appropriate Equations. Equations 9-24 through 9-26 governing the interreflection of light in a three-surface model are

$$M_c = M_{0c} + \rho_c(M_w f_{c \rightarrow w} + M_f f_{c \rightarrow f})$$

$$M_w = M_{0w} + \rho_w(M_c f_{w \rightarrow c} + M_w f_{w \rightarrow w} + M_f f_{w \rightarrow f})$$

$$M_f = M_{0f} + \rho_f(M_c f_{f \rightarrow c} + M_w f_{f \rightarrow w})$$

where

M_c = final ceiling exitance,
 M_w = final wall exitance,
 M_f = final floor exitance,
 M_{0c} = initial ceiling exitance,
 M_{0w} = initial wall exitance,
 M_{0f} = initial floor exitance,
 ρ_c = ceiling reflectance,
 ρ_w = wall reflectance,
 ρ_f = floor reflectance,
 $f_{f \rightarrow c}$ = form factor from the floor to the ceiling,
 $f_{f \rightarrow w}$ = form factor from the floor to the walls,
 $f_{w \rightarrow c}$ = form factor from the walls to the ceiling,
 $f_{w \rightarrow w}$ = form factor from the walls to the walls,
 $f_{w \rightarrow f}$ = form factor from the walls to the floor,
 $f_{c \rightarrow w}$ = form factor from the ceiling to the walls,
 $f_{c \rightarrow f}$ = form factor from the ceiling to the floor.

As discussed above, reciprocity between radiative exchange form factors and the simple geometry of the three-surface model permits six of the seven form factors to be calculated from the single form factor $f_{f \rightarrow c}$, the radiative exchange form factor between floor and ceiling. This is the fraction of flux leaving the ceiling that reaches the floor directly. $f_{f \rightarrow c}$ is calculated using the equation for identical, parallel, directly opposed rectangles.

The initial exitances M_{0c} , M_{0w} , and M_{0f} are determined from

$$M = \frac{\Phi_{\text{onto}} \rho}{\text{area}}$$

where Φ_{onto} is in this case, the flux directly from the skylights onto the surface.

The three simultaneous equations can then be solved for the final exitances M_c , M_w , and M_f . Finally, the illuminance produced at the desk by the ceiling and walls is calculated from

$$E = M_{c \rightarrow p} + M_{w \rightarrow p}$$

where

$c_{c \rightarrow p}$ = configuration factor from the ceiling to the point,
 $c_{p \rightarrow w}$ = configuration factor from the walls to the point.

In this case the configuration factor is for a rectangle to a point in a plane parallel to the plane of the rectangle. This equation is found in Figure 9-3.

Since the sum of the configuration factors from all the surfaces enclosing a point is 1.0,

$$c_{p \rightarrow w} = 1.0 - c_{c \rightarrow p}$$

6. Solve the Equations. The radiative exchange form factor between floor and ceiling, $f_{f \rightarrow c}$, is calculated using Figure 9-5. Substituting the dimensions determined in step 1 into the appropriate equation, it is determined that $f_{f \rightarrow c} = 0.52571$.

We now use the relationships among the other form factors (from Equations 9-28 through 9-31):

$$f_{c \rightarrow f} = f_{f \rightarrow c} = 0.52571,$$

$$f_{c \rightarrow w} = f_{f \rightarrow w} = 1 - f_{c \rightarrow f} = 0.47429,$$

$$f_{w \rightarrow c} = f_{w \rightarrow f} = \frac{A_c}{A_w} (1 - f_{c \rightarrow f}) = 0.33200,$$

$$f_{w \rightarrow w} = 1 - 2f_{w \rightarrow c} = 0.33599,$$

where A_c is the area of the ceiling and A_w is the area of the walls. The equations for M_c , M_w , and M_f become

$$M_c = M_{0c} + 0.80(M_w 0.47429 + M_f 0.52571),$$

$$M_w = M_{0w} + 0.46(M_c 0.33200 + M_w 0.33599 + M_f 0.33200),$$

$$M_f = M_{0f} + 0.20(M_c 0.52571 + M_w 0.47429).$$

The initial exitance of the ceiling, M_{0c} , is zero, since the skylights cannot directly illuminate the ceiling: $M_{0c} = 0.0$. The initial exitance of the floor, M_{0f} , is given by

$$M_{0f} = \frac{\Phi_{\text{skylights} \rightarrow \text{floor}} \rho_f}{A_f}$$

where

$\Phi_{\text{skylights} \rightarrow \text{floor}}$ = flux emitted by the skylights that reaches the floor directly,
 A_f = area of the floor.

The flux from the skylights to the floor is calculated from the total flux leaving the skylights and the radiative exchange form factors from the skylights to the floor:

$$\Phi_{\text{skylights} \rightarrow \text{floor}} = \sum_{i=1}^4 \Phi_{\text{skylight}_i} f_{\text{skylight}_i \rightarrow \text{floor}}$$

The summation is over the four skylights in the room. Since the skylights are identical and placed symmetrically with respect to the calculation point and the center of the room, each emits the same number of lumens, and the form factors from each skylight to the floor are identical. Thus

$$\Phi_{\text{skylights} \rightarrow \text{floor}} = 4 \Phi_{\text{skylight}} f_{\text{skylight} \rightarrow \text{floor}}$$

Φ_{skylight} is calculated from $\Phi_{\text{skylight}} = M_{\text{skylight}} A_{\text{skylight}}$. Thus

$$M_{0f} = \frac{4 M_{\text{skylight}} A_{\text{skylight}} f_{\text{skylight} \rightarrow \text{floor}} \rho_f}{A_f}$$

The skylight exitance M_{skylight} , as calculated in example 4, is 2057 lm/ft². The radiative exchange form factor from a skylight to the floor is calculated from the appropriate equation in Figure 9-6. The resulting value of $f_{\text{skylight} \rightarrow \text{floor}}$ is 0.556. Solving for M_{0f} then, we have

$$M_{0f} = \frac{4(2057)(16)(0.556)(0.20)}{(28)(28)} = 18.7 \frac{\text{lm}}{\text{ft}^2}$$

The initial wall exitance is treated similarly:

$$M_{0w} = \frac{4 M_{\text{skylight}} A_{\text{skylight}} f_{\text{skylight} \rightarrow \text{walls}} \rho_w}{A_w}$$

The radiative exchange form factor from the skylight to the walls is found by closure; that is, all of the flux emitted by a skylight that does not reach the floor must reach the walls: $f_{\text{skylight} \rightarrow \text{walls}} = 1 - f_{\text{skylight} \rightarrow \text{floor}} = 1 - 0.556 = 0.444$. Thus

$$M = \frac{4(2057)(16)(0.444)(0.50)}{(4)(28)(10)} = 26.1 \frac{\text{lm}}{\text{ft}^2}$$

With these three values of initial exitance, the three simultaneous equations become

$$\begin{aligned} M_w &= 26.1 + M_c 0.15372 + M_w 0.15556 + M_f 0.15372 \\ M_f &= 18.7 + M_c 0.10514 + M_w 0.09486 \\ M_c &= 0.0 + M_w 0.37943 + M_f 0.42057 \end{aligned}$$

The solution of these three equations yields $M_c = 25.87$ lm/ft², $M_w = 40.21$ lm/ft², and $M_f = 25.23$ lm/ft².

The configuration factor from the calculation point to the ceiling, $c_{c \rightarrow p}$, is calculated as described in Figure 9-2. Its value is 0.811. By closure, the configuration factor from the calculation point to the walls, $c_{p \rightarrow w}$, equals $1.0 - c_{c \rightarrow p} = 0.189$. Finally, solving for the interreflected illuminance E , we have $E = M_c c_{c \rightarrow p} + M_w c_{p \rightarrow w} = 25.87(0.811) + 40.21(0.189) = 28.76$ fc.

The sum of the direct (from example 4) and interreflected illuminance components is $E_{\text{total}} = 86 + 28.76 = 115$ fc. Thus the calculated value for the illuminance is 115 fc for the prescribed time, location, and sky.

Example 6: Calculation of Luminances Produced by a Point Source

This example illustrates the task lighting analysis of a desk. A small desk luminaire is to be used for lighting desks in workstations (Figure 9-51).

1. Determine the Quantity to be Calculated. The analysis of the performance of a task light on a desk consists, in part, of a determination of the luminance of a white piece of paper.

2. Identify Luminaires and the Information Describing Them. The luminaire used is a single 13-W compact fluorescent lamp with a reflector that produces a very directional luminous intensity distribution. The luminaire is 6 in. long, 3 in. wide, and 1.5 in. high. It is mounted on a movable arm designed to permit it to be placed off to the side of the desk. The photometric data are shown in Figure 9-52.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. The luminance of the paper is assumed to be diffuse, so the luminance calculation requires only a de-

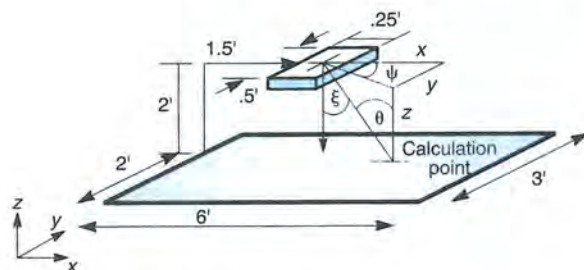


Figure 9-51. Desk layout for Example 6.

Figure 9-52. Luminous Intensity Distribution of Desk Luminaire

Elevation Angle θ	Intensity (cd) at Azimuthal Angle ψ				
	0.0°	22.5°	45.0°	67.5°	90.0°
0.0°	450	450	450	450	450
5.0°	453	457	453	445	442
15.0°	437	446	450	454	451
25.0°	406	422	447	470	478
35.0°	362	391	443	497	523
45.0°	302	350	448	551	592
55.0°	233	310	474	624	678
65.0°	158	284	505	651	691
75.0°	81	263	432	529	559
85.0°	20	134	178	192	193
90.0°	1	4	5	8	10

termination of the illuminance and a measurement of the paper's diffuse reflectance.

As shown in Figure 9-51, the luminaire arm is mounted at the side of a desk whose dimensions are 6 × 3 ft. The luminaire is located at a height of 2 ft above the desk surface, 1.5 ft to the left of the center of the desk, and 2 ft from the front of the desk. The distance from the center of the luminaire to the center of the desk is given by

$$D = \sqrt{x^2 + y^2 + z^2} = \sqrt{1.5^2 + 0.5^2 + 2^2} = 2.55 \text{ ft}$$

This distance is larger than 5 times the maximum luminous dimension of the luminaire (0.5 ft), so the inverse square cosine law for the illuminance from a point source can be used.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The geometric dimensions are shown in Figure 9-51. The white paper is a diffusely reflecting object with a reflectance $\rho = 0.83$.

5. Determine Appropriate Equations. The luminance (L) of a diffusely reflecting surface is given by the following formula:

$$L = \frac{M}{\pi} = \frac{\rho_{\text{paper}} E}{\pi}$$

The illuminance at the center of the desk is given by

$$E = \frac{I(\theta, \psi) \cos \theta}{D^2}$$

The luminous intensity distribution data are shown in Figure 9-52. The angles required to determine the luminous intensity are calculated as follows from geometric principles (Figure 9-51):

$$\begin{aligned} \theta &= \arctan \left(\frac{\sqrt{x^2 + y^2}}{z} \right) \\ \psi &= \arctan \left(\frac{y}{x} \right) \end{aligned}$$

The incident angle ξ is given by the following expression:

$$\xi = \arctan \left(\frac{\sqrt{x^2 + y^2}}{z} \right)$$

6. Solve the Equations. First, the illuminance produced by the luminaire is calculated. Using the dimensions in Figure 9-51,

$$\theta = \arctan \left(\frac{\sqrt{1.5^2 + 0.5^2}}{2} \right) = 38.3^\circ$$

$$\psi = \arctan \left(\frac{0.5}{1.5} \right) = 18.4^\circ$$

Linearly interpolating in the table of luminous intensities (Figure 9-52), the intensity at $(\theta = 38.3^\circ, \psi = 18.4^\circ)$ has a value of 356 cd.

The incident angle is given by

$$\xi = \arctan \left(\frac{\sqrt{1.5^2 + 0.5^2}}{2} \right) = 38.3^\circ$$

The illuminance E is calculated as follows:

$$E = \frac{I(\theta, \psi) \cos \theta}{D^2} = \frac{356 \cos (38.3^\circ)}{1.5^2 + 0.5^2 + 2^2} = 42.9 \text{ fc}$$

The luminance of the paper is

$$L_{\text{paper}} = \frac{\rho_{\text{paper}} E}{\pi} = \frac{(0.83)(42.9)}{\pi} = 11.4 \text{ cd / ft}^2$$

7: Calculation of Contrast Produced on Printed Material

This example also illustrates the task lighting analysis of a desk. A small desk luminaire is to be used for task lighting desks in workstations.

1. Determine the Quantity to be Calculated. The analysis of the performance of a task light on a desk consists, in part, of a determination of the visual task contrast that is produced on the horizontal desk surface. The contrast determined here is that for black print on white glossy paper, such as is commonly found in journals and magazines.

2. Identify Luminaires and the Information Describing Them. The same luminaire is used for this example was for Example 6. The luminous intensity distribution is shown in Figure 9-52.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. Calculating the contrast requires determining the luminance of both the task and its background. Neither the paper nor the print ink is assumed to have a diffuse reflectance for this example. Therefore, the calculation

of these luminances requires both the illuminance and the bidirectional reflectance distribution function (BRDF) of the task and its background.

The layout of the task is shown in Figure 9-53. As calculated in Example 6, the distance from the task (at the center of the desk) to the center of the luminaire is 2.55 ft, which is larger than 5 times the maximum luminous dimension of the luminaire. Thus the inverse square cosine law is valid in this case.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The necessary dimensions are shown in the figure. The BRDFs for the paper and for the printed ink are shown in Figures 9-54 and 9-55, for a typical viewing angle of 10° from vertical. The irregular spacing of the azimuth and declination angles in the BRDF tables reflects the degree of specularly for the material. Where angles are spaced closer together, the BRDF is more sensitive to small changes in these angles.

5. Determine Appropriate Equations. The luminance contrast C of a task is given by

$$C = \frac{|L_b - L_t|}{L_b}$$

where L_b is the luminance of the background and L_t is the luminance of the target. In this example, the luminances are of nondiffusely reflecting surfaces. The luminance of a nondiffusely reflecting surface illuminated by an unpolarized source is described earlier in this chapter, and is

$$L(\theta_v) = \sum_i \sum_j E(\theta_i, \psi_j) f_r(\theta_v; \theta_i, \psi_j)$$

where

θ_v = viewing declination angle, in this case equal to 10° ,

θ_i = incident declination angle,

ψ_j = incident azimuthal angle, measured from the plane containing the direction of view and given by $\psi_j = 90^\circ + \arctan(y/x)$.

The sum is taken over all the discrete values of illuminance. The number of discrete steps determines the accuracy of the

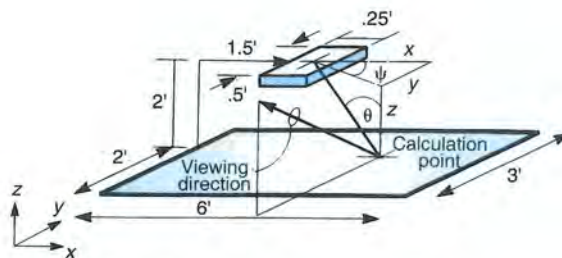


Figure 9-53. Desk lamp drawing for Example 7.

Figure 9-54. Partial Bidirectional Reflectance Distribution Function (BRDF) Data for White Paper*

Azimuth	BRDF (sr ⁻¹) at Declination					
	24°	28°	34°	44°	52°	60°
0°	0.226	0.221	0.215	0.216	0.205	0.194
130°	0.240	0.226	0.220	0.217	0.208	0.197
150°	0.249	0.231	0.224	0.214	0.208	0.196
160°	0.252	0.231	0.221	0.214	0.200	0.196
170°	0.253	0.233	0.222	0.216	0.212	0.196
176°	0.250	0.234	0.223	0.216	0.206	0.197
177°	0.261	0.235	0.224	0.217	0.205	0.198
178°	0.262	0.236	0.223	0.218	0.211	0.198
179°	0.263	0.235	0.223	0.219	0.213	0.200
180°	0.263	0.234	0.222	0.219	0.210	0.193

*Viewing declination angle = 10°, viewing azimuth angle = 0°.

approximation. The step size in these approximations is determined by the need to model high gradients of either the illuminance or the BRDFs. In the present case, the largest declination angle subtended by the luminaire to the calculation point is 6.9°, and the largest azimuthal angle subtended by the luminaire is 19.9°. The azimuthal and declination incident angles from the center of the luminaire are used to determine the region of the BRDFs being used. Examination of this region reveals whether discretization is necessary for an illuminating field that measures 6.9° × 19.9°.

6. Solve the Equations. The illuminance at the center of the desk is 42.9 fc, as shown in example 6. The luminances of task and background require determining the BRDFs of the paper and of the printed ink at the specified angles. The incident azimuthal angle ψ_i must be determined: $\psi_j = 90^\circ + \arctan(1.5/0.5) = 161.5^\circ$.

The incident declination angle has been determined to be 38.3° in Example 6. Given the viewing angle of 10°, the BRDF tables in Figures 9-54 and 9-55 for the paper and ink are interpolated to obtain the values $f_{\text{ink}}(10^\circ; 38.3^\circ, 161.5^\circ) = 0.0001$ and $f_{\text{paper}}(10^\circ; 38.3^\circ, 161.5^\circ) = 0.2182$.

Figure 9-55. Partial BRDF Data for Black Printed Ink*

Azimuth	BRDF (sr ⁻¹) at Declination					
	22°	28°	36°	44°	52°	60°
0°	0.004	0.003	0.002	0.001	0.000	0.000
130°	0.013	0.002	0.000	0.000	0.000	0.000
150°	0.034	0.006	0.000	0.000	0.000	0.000
160°	0.056	0.010	0.000	0.000	0.000	0.000
170°	0.089	0.015	0.001	0.000	0.000	0.000
176°	0.109	0.018	0.001	0.000	0.000	0.000
177°	0.111	0.019	0.001	0.000	0.000	0.000
178°	0.113	0.019	0.002	0.000	0.000	0.000
179°	0.116	0.020	0.002	0.000	0.000	0.000
180°	0.118	0.020	0.002	0.000	0.000	0.000

*Viewing declination angle = 10°, viewing azimuth angle = 0°.

The units of BRDFs are inverse steradians (sr⁻¹). The luminance of the ink at the calculation point is then $L_{\text{ink}} = E(\theta_i, \psi_i) f_r(\theta_v; \theta_i, \psi_i) = (42.9 \text{ fc})(0.0001 \text{ sr}^{-1}) = 0.0043 \text{ cd/ft}^2$. The luminance of the paper at the calculation point is $L_{\text{paper}} = E(\theta_i, \psi_i) f_r(\theta_v; \theta_i, \psi_i) = (42.9 \text{ fc})(0.2182 \text{ sr}^{-1}) = 9.36 \text{ cd/ft}^2$. The luminance contrast of the task and background is then

$$C = \frac{|9.36 - 0.0034|}{9.36} = 0.999$$

Calculations of contrast for the extreme azimuth and declination angles subtended by the luminaire result in the following contrasts at the calculation point:

$$\begin{aligned} C(38.3^\circ + 3.45^\circ, 161.5^\circ + 9.95^\circ) &= C(41.75^\circ, 171.45^\circ) = 0.999 \\ C(38.3^\circ + 3.45^\circ, 161.5^\circ - 9.95^\circ) &= C(41.75^\circ, 151.55^\circ) = 1.000 \\ C(38.3^\circ - 3.45^\circ, 161.5^\circ + 9.95^\circ) &= C(34.85^\circ, 171.45^\circ) = 0.986 \\ C(38.3^\circ - 3.45^\circ, 161.5^\circ - 9.95^\circ) &= C(34.85^\circ, 151.55^\circ) = 0.970 \end{aligned}$$

Each of these lies within 10% of the contrast calculated using a single point at the center of the luminaire, so discretization of the luminaire into several elements is not required.

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Quality of the Visual Environment

III

10. Quality of the Visual Environment
IESNA Lighting Design Guide