LIGHTING

NATURE OF LIGHT

Electromagnetic radiation in the visible spectrum, also called light waves, has wavelengths (λ) that lie between 400 nm and 750 nm or between 4000 Å and 7500 Å (10 Å = 10 Angstrom = 1 nm). The velocity of light = c = 3×10^8 m/s, and the frequency f of a light wave is given by the equation $f = c/\lambda$ Hz (or cycles/s). An illumination scheme must be designed within these parameters because the human eye "senses" only visible radiation.

Figure 1 shows the electromagnetic spectrum, and Fig. 2 shows the narrow band of the electromagnetic spectrum that contains visible radiation. Figure 2 ranges from 2500 Å to 30,000 Å and includes ultraviolet and infrared regions of the spectrum.

Steradians. Because light is radiated from a source in three-dimensional space, it is necessary to define the quantity known as a *solid angle*. The unit of the *solid angle* is the steradian. A *plane angle* θ is defined as the space between two converging lines. The unit of θ is in radians. A radian is defined as the angle subtended at the center of a circle by an arc whose length is equal to the radius. Figure 3 shows the difference between a plane angle and a solid angle. A full circle measures 2π radians. However, to define a solid angle (symbol ω), we need to consider the volume enclosed by an infinite number of lines that lie on a surface and meet at a single point. Extending the above definition for a plane angle, it is easily observed that a sphere, instead of a circle, is the basis for defining a solid angle. The surface area of a sphere is $4\pi r^2$. Therefore a total solid angle subtended by a point in all possible directions is 4π steradians. In other words, radians = (arc/radius) whereas, steradians = (area/(radius)^2).

Luminous Flux. Luminous flux Φ is defined as the rate of flow of light. This is an important definition because radiated energy varies in its ability to produce visual effects and sensation. The *lumen* is the unit of luminous flux, and light sources are rated in lumens. One lumen is equal to the flux through one unit of a solid angle steradian from a point light source

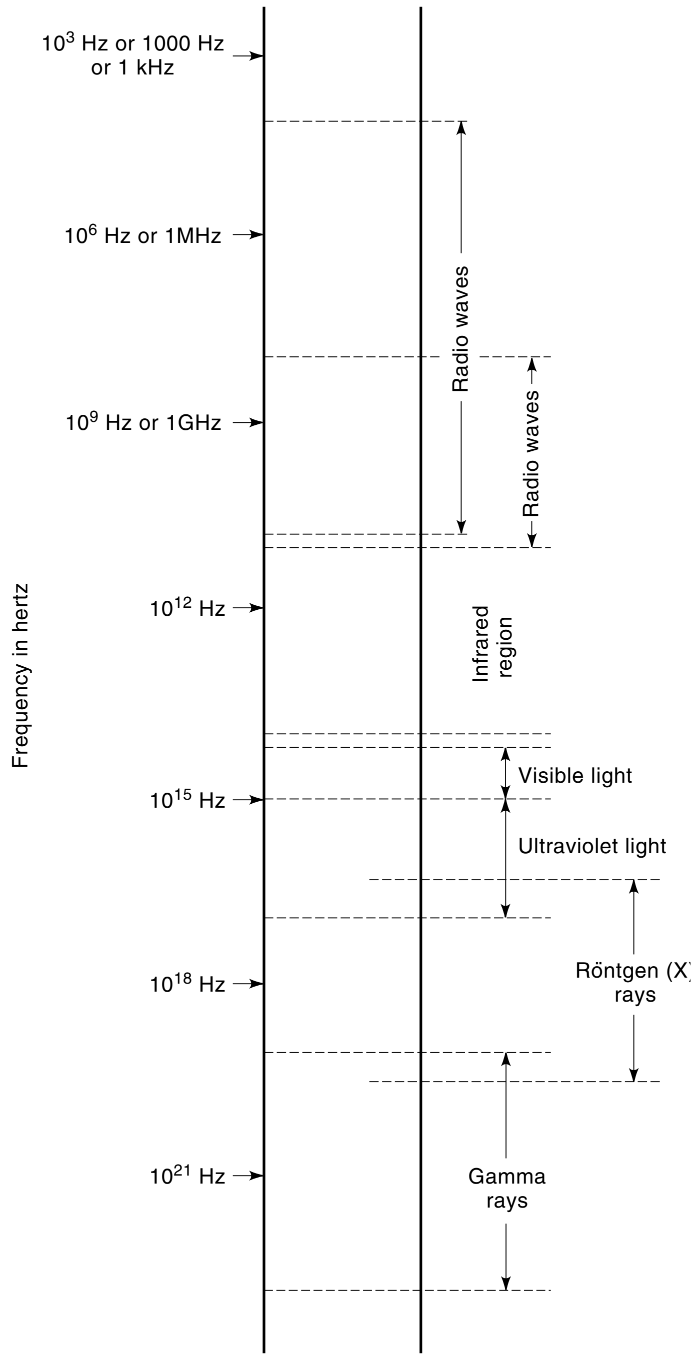

Figure 1. Electromagnetic spectrum.

of one candela. Mathematically, it is expressed as

$$\Phi = \frac{dQ}{dt}$$

Two sources may radiate equal amounts of energy however, they may emit different amounts of luminous flux.

Luminous Efficacy. The effectiveness of light sources is studied using luminous efficacy, which is the ratio of the total luminous flux in lumens to the total input power in watts. Formerly the term "luminous efficiency" was used to denote this ratio. Assuming constant output over the entire visible

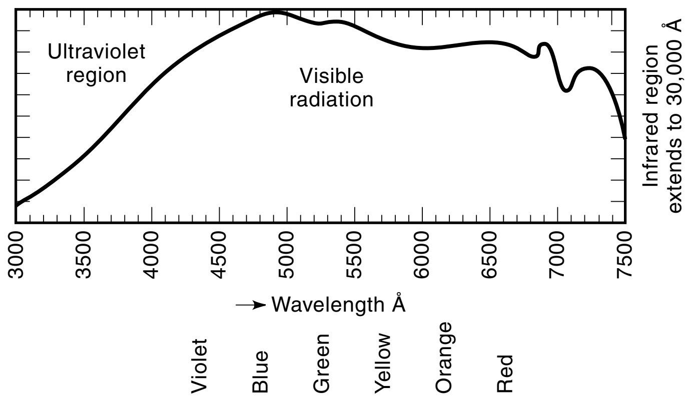

Figure 2. Sun's radiation.

spectrum, the "ideal" white source is supposed to possess a maximum luminous efficacy of approximately 220 lm/W. The response of "visual sensation" of a normal human eye depends on the wavelength of the radiant energy in the visible region of the spectrum. Therefore, a term called "spectral luminous efficacy," or "luminosity factor" has also been defined, when spectral distribution of the energy is to be considered for more detailed mathematical calculations. Figure 4 shows that the relative spectral luminous efficacy of a normal human eye attains a maximum at approximately 555 nm (yellow-orange region).

Candela. This was formerly known as "candle." Originally it was defined in terms of the strength of a standard candle flame. Now, the candela is defined as the luminous intensity of a source that emits monochromatic radiation at a frequency of 540×10^{12} Hz or a wavelength equal to 555 nm and of radiant intensity in the chosen direction equal to 1/683 watt per steradian.

Luminous Intensity. Luminous intensity is the luminous flux per unit solid angle in a given direction. *Candlepower* is luminous intensity expressed in candelas. The definition of luminous intensity strictly applies to a *point source of light.* Mathematically this is written as

$$I = \frac{d\Phi}{d\omega}$$

Illuminance. Illuminance is the density of luminous flux incident on a surface. Assuming that the surface is uniformly

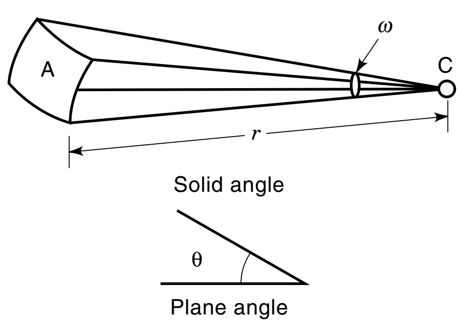

Figure 3. Defining solid angle and plane angle.

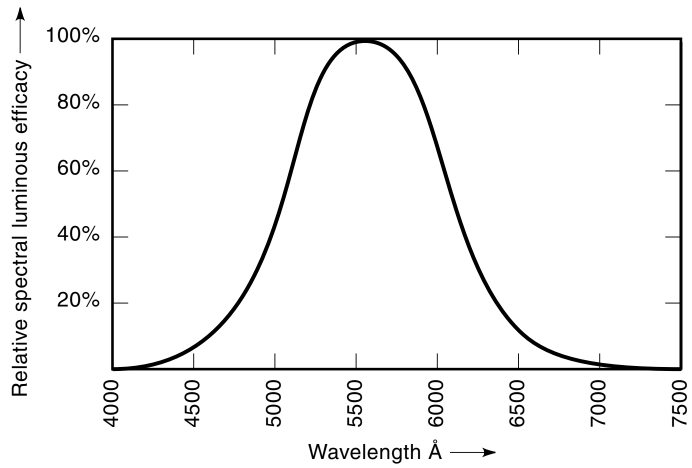

Figure 4. Sensitivity curve of the eye (normal vision-cone cells).

illuminated, it is the quotient of the luminous flux divided by the area of the surface.

Illuminance is an alternative term for illumination and expresses the density of luminous flux incident on a surface. If A is the area of illuminated surface, then

$$E = \frac{d\Phi}{dA}$$

It can also be written as

$$\Phi = \int E\, dA$$

If E is uniform over the area A, then

$$\Phi = EA$$

E is also directly proportional to the luminous intensity I, or, mathematically,

$$E \propto I$$

1 lm/ft^2 is also called one *foot-candle* (fc). 1 lm/m^2 is called a *lux* (lx). 1 lm/cm^2 is called a *phot* (ph). 1 fc = 10.76 lx, or 1 lx = 0.0929 fc. Table 1 shows typical recommended ranges of illuminance levels for floodlighting.

Luminance. Many sources are not point sources and therefore another concept called *photometric brightness* or *luminance* is used. Luminance is defined as the ratio of the differential luminous intensity to the projected differential area

Table 1. Floodlighting Illuminance Levels: An Example of Typical Values

	Recommended Level, Lux[a]
Low-activity driveway	8–15
Parking facilities	40–50
Building construction	80–120
Gasoline service station	150–300
Landmarks and monuments	150–500
Dark building exteriors	200–500
Billboards and posters	500–1000

[a] Actual values vary. Excessive contrast may cause ocular fatigue.

from the direction of observation. Mathematically, this is written as

$$L = \frac{dI}{\cos\alpha\, dA}$$

where L = luminance in candela per square meter, dI = the differential luminous intensity, dA = a differential segment of the surface, and α = the angle between the normal to the direction of observation.

The unit of luminance is expressed in candela per square meter and is called a nit (abbreviated nt). Because this involves a large area of 1 m^2, a stilb is defined as 1 cd/cm^2. 1 lm/cm^2 is also called one lambert. 1 lm/ft^2 equals 1 foot-lambert. Luminance and illuminance are defined differently.

$$E = \frac{d\Phi}{dA}$$
$$I = \frac{d\Phi}{d\omega}$$
$$L = \frac{dI}{\cos\alpha\, dA} = L = \frac{d^2\Phi}{[(d\omega)(\cos\alpha\, dA)]}$$

Luminaires. Luminaires are complete lighting units. They consist of one or more lamps or bulbs, the lamp shade or reflector that is designed to distribute or reflect the light beams and to position and protect the lamps or bulbs, and the necessary wiring and other electrical hardware, such as a high voltage transformer.

The Inverse Square Law. The illumination of a surface is inversely proportional to the square of its distance from the source. Mathematically $E \propto (1/r^2)$ where r = distance. The inverse square law is useful in calculating the direct component of illuminance. The inverse square law may be applied to calculate the foot candles on a horizontal plane (for example, a factory floor) or a vertical plane (for example, a marker board in a classroom).

Lambert's Cosine Law. Illumination is directly proportional to the cosine of the angle between the normal (from the source to the illuminated surface) and the direction of incident flux. Consider Fig. 5(a) wherein the flux Φ is incident on a surface area A. The illumination of the surface in this position is given by $E_1 = \Phi/A$. Now consider Fig. 5(b) wherein the surface has been tilted by an angle θ. Now the flux incident on it is $\Phi \cos\theta$. The illumination in this new position is $E_2 = \Phi \cos\theta/A$ or $E_2 = E_1 \cos\theta$. Because $E = (I/r^2)$, we can generalize this as $E = I\cos\theta/r^2$. This can be further extended to calculate illumination at different locations. Consider Fig. 5(c) wherein a lamp of uniform luminous intensity is suspended at a height r above the surface under consideration. Illumination directly beneath the lamp at location X is

$$E_X = I/r^2$$

or

$$I = E_X(r^2)$$

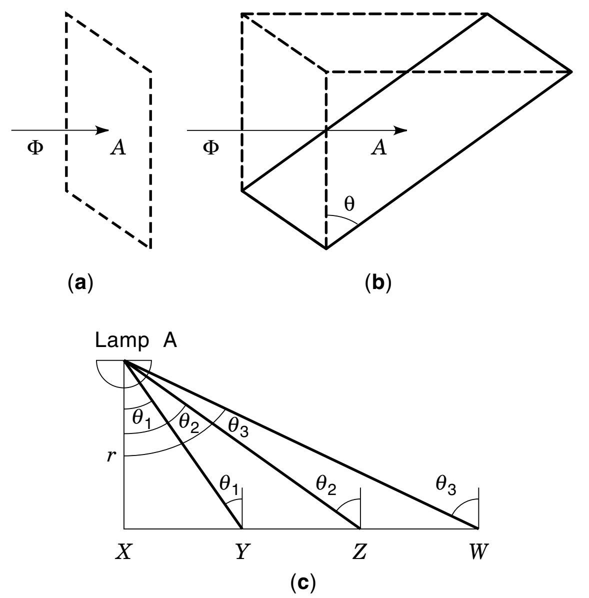

Figure 5. Illustrating Lambert's cosine law.

Illumination at location Y is

$$E_Y = [(I\cos\theta_1)/(AY)^2]$$

But

$$\cos\theta_1 = r/AY$$

Therefore

$$E_Y = [(Ir)/(AY)^3] = [(E_X(r^2)r)/(AY)^3] = [(E_X r^3)/(AY)^3]$$

In other words,

$$E_Y = E_X \cos^3\theta_1$$

Similarly,

$$E_Z = E_X \cos^3\theta_2$$
$$E_W = E_X \cos^3\theta_3$$

Candlepower. The candlepower of a source is defined as the number of lumens emitted in a unit solid angle in a given direction. Candlepower is luminous intensity expressed in candelas.

Brightness. Brightness is defined as the luminous intensity per unit projected area of the surface in a given direction. Brightness depends on the luminance and also the sensation it produces on the eye. It depends on how the eye adapts to the conditions of observation because it refers to the intensity of sensation that results from viewing the luminaire or illuminated surface.

Lambert. A lambert is a unit of brightness equivalent to the brightness of a perfectly diffusing surface that emits or reflects one lumen per square centimeter. The unit is named after Johann Heinrich Lambert (1728-1777), German physicist and astronomer.

Reflectance. Reflectance is defined as the ratio of reflected flux to incident flux. It is very important to know the spectral characteristics of the source involved to calculate the reflectance of a surface. Reflectance depends on the angle of incidence of the source flux and also the angle of reflection from the viewer's position. The symbol for reflectance is ρ.

Transmittance. Transmittance is defined as the ratio of transmitted flux to incident flux. Just as in the case of *reflectance,* it is very important to know the spectral characteristics of the source involved to calculate the transmittance of a surface. Transmittance depends on the angle of incidence of the source flux and the angle of reflection from the viewer's position. The symbol for transmittance is τ.

Absorptance. Absorptance is defined as the ratio of the flux absorbed by a medium to the incident flux. A black body absorbs more light, whereas a white body reflects more light. The symbol for absorptance is α. It is easily observed that $\rho + \tau + \alpha = 1$.

TYPES OF LAMPS

Illumination levels have been established by the Illuminating Engineering Society (IES) in its *IES Lighting Handbook: Reference and Applications Volume.*

Incandescent Lamps

These are the cheapest form of light bulbs used to produce light. The glass bulb is evacuated and is filled with an inert gas, such as nitrogen or argon, to reduce the rate of evaporation of the heated element. Halogen gases are becoming more popular. Electric current is passed through a filament that possesses a very high melting point, like tungsten, for example. This filament eventually becomes "white-hot" and emits visible radiation. With the use of bromine or iodine vapors inside a quartz bulb, it is possible to create a halogen-regenerative cycle. Lengthy, slender tungsten filaments are very fragile, and therefore such lamps may have a short life besides providing the lowest luminous efficacy. The passage of an electric current through a gas or vapor is the principle behind the operation of arc lamps and vapor lamps. Projection equipment also utilizes special designs to exploit the efficient utilization of luminous flux.

Fluorescent Lamps

These are electric discharge lamps. The energy discharged is directed to impinge on a coating of phosphor, which in turn produces visible radiation. The chemical composition of the phosphor coating determines the color of the light produced. Most of these lamps are tubular. However, U-shaped and circular-shaped bulbs are available. They normally operate with a starter and a reactance ballast choke. Electronic ballasts increase lamp efficacy and reduce input power. They draw relatively small amounts of current in the range of a few hundred milliamperes depending on the type of lamp. They consume less power, but provide more light output.

High-Intensity Discharge Lamps

An arc tube made out of fused silica or polycrystalline alumina normally confines the electric discharge in a mercury vapor lamp or a sodium vapor lamp. Again this tube is enclosed in an outer jacket that may or may not have a phosphor coating.

Illumination for Instruments

Although small incandescent lamps are still used for some instrument displays, light-emitting diodes, liquid-crystal displays, and plasma displays have made a deep impact on instrument illumination and data displays. The cathode ray tube is another method widely used for displaying data.

LIGHTING DESIGN

Productivity on a factory floor or in a corporate office can suffer if lighting schemes are not designed properly. The color and the amount of light output have a significant impact on worker attitudes. People may be annoyed, experience discomfort, or suffer from impaired vision because of poor lighting. Care should be taken to ensure that unnecessary glare, unwanted shadows, and undesired reflection are eliminated. Appropriate and adequate lighting should be provided.

Luminaires are designed to distribute light either downward or upward with reference to a horizontal plane.

General lighting systems are classified as follows:

- Direct lighting: More than 90% downward toward the work surface and less than 10% upward away from the work surface
- Semidirect lighting: More than 60% downward toward the work surface and less than 40% upward away from the work surface
- Semi-indirect lighting: Less than 40% downward toward the work surface and more than 60% upward away from the work surface
- Indirect lighting: Less than 10% downward toward the work surface and more than 90% upward away from the work surface
- Diffused lighting: Tries to accomplish an approximately 50% split

A precision watchmaker or an engraver may choose to have direct lighting, whereas a movie auditorium may have indirect or semi-indirect lighting.

In its *Lighting Design Handbook,* the Illuminating Engineering Society of North America (IESNA) recommends illuminance ranges for various activities. If the task involved involves simple benchwork, packaging, or assembly, 300 to 500 lux may be adequate. However, extra fine, exacting or precision work may demand as much as 10,000 lux.

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LIGHTING BALLAST. See Lighting control.