Chapter 5.

LUMINOUS MEASUREMENTS

Two basic elements intervene in lighting engineering: both the source of light and the object to be illuminated.
In the present chapter, we will deal with fundamental measurements and units used to evaluate and compare the quality and effects of sources of light.

5.1. Luminous flux (luminous output)

Energy transformed by light sources cannot be totally taken advantage of for light production. For example, an incadescent lamp consumes a certain amount of electric energy which is transformed into radiant energy. Out of this, only a small amount (about 10%) is perceived by the human eye as light, while the rest of it is lost as heat.
A luminous flux produced by a source of light is the total amount of light, either emitted or radiated in all directions in one second. More precisely, a source of light **luminous flux** is *radiated energy received by the human eye depending on its sensitivity curve, and which is transformed into light for a second.*
Luminous flux is represented by the Greek letter Φ and is measured in **lumens** (lm). Lumen is the luminous flux of the monochromatic radiation characterised by a value frequency of $540 \cdot 10^{12}$ Hz. and a radiant power flux of 1/683 W. One 555 nm. wavelength radiant energy watt in the air equals 683 lm approximately.

Luminous flux measurement

Luminous flux measurement is conducted by means of an adjusted photoelement depending on the phototopic sensitivity curve of the standard eye to the monochromatic radiations, incorporated to a hollow sphere known as *Ullbricht's sphere* (Fig. 1). The source to be measured is placed inside it. Manufacturers provide lamp flux in lumens for nominal potency.

Figure 1. Ullbricht's sphere.

Luminous performance (Luminous efficacy)

Luminous performance of a source of light indicates the flux emitted by this source per unit of electrical output consumed to obtain it. It is represented by the Greek letter ε, and it is measured as **lumen/watt** (lm/W).
The formula which expresses luminous efficacy is:

$$\varepsilon = \frac{\Phi}{P} \quad (\text{lm/W})$$

If a lamp was to be manufactured which transformed all the consumed electrical output into light at one 555 nm. wavelength without losses, such a lamp would have the highest performance possible. Its value would be 683 lm/W.

5.2. Amount of light (Luminous energy)

In a similar way to electrical energy, which is determined by the electrical output in the time unit, the amount of light or luminous energy is determined by the luminous output or luminous flux emitted by the time unit.

The amount of light is represented by the letter **Q**, and is measured as lumen per hour (lm · h).

The formula which expresses the amount of light is the following:

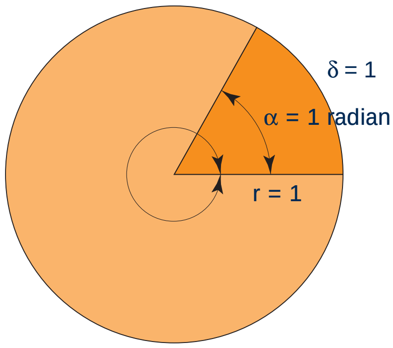
$$\mathbf{Q} = \Phi \cdot t \quad (\text{lm} \cdot \text{h})$$

5.3. Luminous intensity

This measurement is solely understood as referred to a specific direction and contained in a w solid angle.

In the same way that a plane angle measured in radians corresponds to a surface, a solid or stereo angle corresponds to a volume measurement and is measured in *stereoradians.*

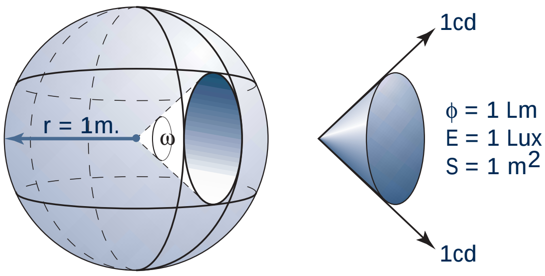
The radian is defined as the plane angle within an arc of a circle, equal to the radius of the circle. (Fig. 2).



α (total) = 2 π radians

Figure 2. Plane angle.

The stereoradian is defined as the solid angle which corresponds to a spherical cap whose surface equals the square of the sphere radius (Fig. 3).



ω (total) = 4π stereoradians

Figure 3. Solid angle.

Luminous output of a source of light in one specific direction *equals the ratio between the luminous flux contained in whatever solid angle whose axis coincides with the considered direction.* Its symbol is I, and its unit of measurement is the candela (cd). The formula which expresses it is the following:

$$I = \frac{\Phi}{\omega} \quad (\text{lm/sr})$$

Candela is defined as *the luminous intensity of a specific source which emits luminous flux equal to one lumen in a solid angle per stereoradian (sr).*

According to the I.S.*, candela may also be defined as the luminous intensity in a certain direction, from a source which emits monochromatic radiation with a frequency of $540 \cdot 10^{12}$ Hz, and whose energy intensity in the aforementioned direction is 1/683 watts per stereoradian.

5.4. Illuminance (Luminous level)

Illuminance or luminous level of a surface is the *ratio between the luminous flux received by the surface to its area.* It is represented by the letter **E**, and its unit is the lux (lx).
The formula which expresses illuminance is:

$$E = \frac{\Phi}{S} \quad (lx = lm/m^2)$$

Thus, according to the formula, the higher the luminous flux incident on a surface, the higher its illuminance. Also, for the same given incident luminous flux, illuminance will be higher as surface decreases.
According to the I.S., lux may be defined as the *illuminance of a certain surface which receives a luminous flux of one lumen, spread over one square meter of its surface.*

Lighting level measurement

Luminous level measurement is conducted with a special device known as foot- candle metre. It consists of one photoelectric cell which generates a weak eletric current when light strikes its surface, thus, increasing according to light incidence. Such current is measured by means of an analogic or digital miliammeter, calibrated directly in lux (Fig. 4).

Figure 4. Foot- candle metre.

5.5. Luminance

Luminance is the *effect which produces a surface on the retina of the eye, both coming from a primary source which produces light, or from a secondary source or surface which reflects light.*
Luminance measures brightness for primary light sources as well as for sources constituting illuminated objects. This term has substituted the concepts of brightness and lighting density. Nevertheless, it is interesting to remember that the human eye does not perceive colours but brightness, as a colour attribute. Light perception is, in fact, the perception of differences in luminance. Therefore, it may be stated that the eye perceives luminance differences but not illuminance ones (provided that we have the same lighting, different objects have different luminance since they have different reflection characteristics).
Luminance of an illuminated surface is the ratio between *luminance of a source of light in a given direction, to the surface of the projected source depending on such direction.*

*I.S. ⇒ International System.

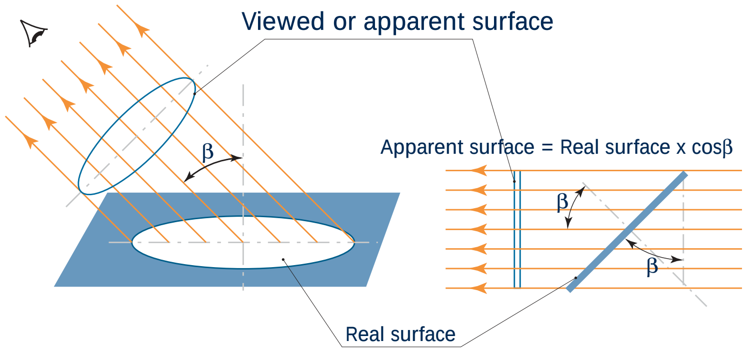


Figure 5. Surface luminance.

The projected area is seen by the observer in the direction of the luminous intensity. This area is calculated by multiplying the illuminated real surface by the cosine angle forming the normal with the direction of the luminous intensity (Fig. 5).
Represented by the letter L, its unit is the candela/square metre called "nit (nt)", with one submultiple, the candela/square centimetre or "stilb", used for high luminance sources.

$$1nt = \frac{1cd}{1m^2} \quad ; \quad 1stilb = \frac{1cd}{1cm^2}$$

The formula which expresses it is the following:

$$L = \frac{I}{S \cdot \cos\beta}$$

where:
$S \cdot \cos\beta$ = Apparent surface.
Luminance is independent from the observation distance.

Luminance measurement

Luminance measurement is conducted by means of a special device called a luminancemetre or nitmeter. It is based on two optical systems, directional and measurement systems, respectively. (Fig. 6).
The directional system is oriented in such a way that the image coincides with the point to be measured. Once it has been oriented, the light that reaches it is transformed into electric current. Its values are measured in cd/m^2.

Figure 6. Luminancemeter.

5.6. Other interesting luminous measurements

5.6.1. Utilization coefficient

Ratio between the luminous flux received by a body and the flux emitted by a source of light.

Unit ⇒ %

Symbol ⇒ η

Ratio ⇒ $\eta = \frac{\Phi}{\Phi_e}$

5.6.2. Reflectance

Ratio between the flux reflected by a body (with or without diffusion) and the flux received.

Unit ⇒ %

Symbol ⇒ ρ

Ratio ⇒ $\rho = \frac{\Phi_r}{\Phi}$

5.6.3. Absorptance

Ratio between the luminous flux absorbed by a body and the flux received.

Unit ⇒ %

Symbol ⇒ α

Ratio ⇒ $\alpha = \frac{\Phi_a}{\Phi}$

5.6.4. Transmittance

Ratio between the luminous flux transmitted by a body and the flux received.

Unit ⇒ %

Symbol ⇒ τ

Ratio ⇒ $\tau = \frac{\Phi_t}{\Phi}$

5.6.5. Average uniformity factor

Ratio between minimum to medium illuminance in a lighting installation.

Unit ⇒ %

Symbol ⇒ U_m

Ratio ⇒ $U_m = \frac{E_{min}}{E_{med}}$

5.6.6. Extreme uniformity factor

Ratio between minimum to maximum illuminance in a lighting installation.

Unit ⇒ %

Symbol ⇒ U_e

Ratio ⇒ $U_e = \frac{E_{min}}{E_{max}}$

5.6.7. Longitudinal uniformity factor

Ratio between longitudinal minimum to maximum luminance in a lighting installation.

Unit ⇒ %

Symbol ⇒ U_L

Ratio ⇒ $U_L = \frac{L_{longitudinal\ min}}{L_{longitudinal\ max}}$

5.6.8. Overall luminance uniformity

Ratio between minimum to medium illuminance in a lighting installation.

Unit ⇒ %

Symbol ⇒ U_0

Ratio ⇒ $U_0 = \frac{L_{min}}{L_{med}}$

5.6.9. Maintenance factor

Coefficient indicating the preservation degree of an installation.

Unit ⇒ %

Symbol ⇒ F_m

Ratio ⇒ $F_m = F_{pl} \cdot F_{dl} \cdot F_t \cdot F_e \cdot F_c$

F_{pl} = lamp position factor

F_{dl} = lamp depreciation factor

F_t = temperature factor

F_e = ignition equipment factor

F_c = installation preservation factor

5.7. Luminous measurement graphic representation

The collection of luminous intensity emitted by a source of light in all directions is known as *luminous distribution.* The sources of light used in practice have a more or less large luminous surface, whose radiation intensity is affected by the construction of the source itself, presenting various values in these scattered directions.

Special devices (like the Goniophotometer) are constructed to determine the luminous intensity of a source of light in all spatial directions in relation to a vertical axis. If luminous intensity (I) of a source of light is represented by vectors in the infinite spatial directions, a volume representing the value for the total flux emitted by the source is created. Such a value may be defined by the formula below:

$$\Phi = \int_v \vec{I} \cdot d\vec{\omega}$$

Photometric solid is the solid obtained. Fig. 7 shows an incasdescent lamp *photometric solid*.

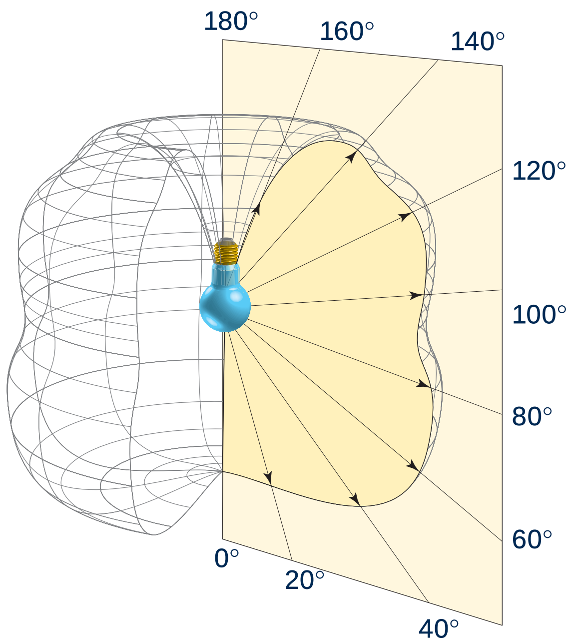


Figure 7. Incandescent lamp photometric solid.

If a plane passes through the symmetric axis of a source of light, for example, a meridional plane, a section limited by a curve, known as *photometric curve,* or luminous distribution curve is obtained (Fig. 8).

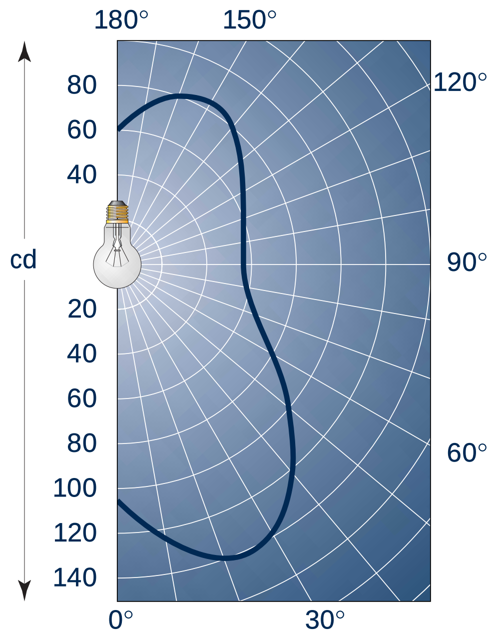


Figure 8. Photometric curve for an incandescent lamp.

By reviewing the photometric curve of a source of light, luminous intensity in any direction may be determined very accurately. This data are necessary for some lighting calculations.

Therefore, spatial directions through which luminous radiation is irradiated may be established by two coordinates. One of the most frequently used coordinate systems to obtain photometric curves is the “C - γ” represented in Fig. 9.

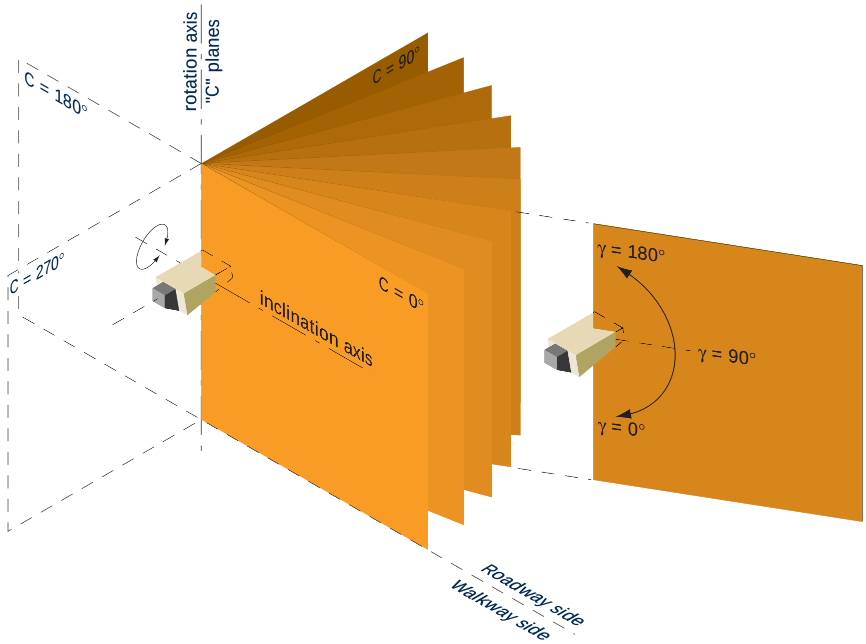


Figure 9. C - γ coordinate system.

Photometric curves refer to an emitted luminous flux of 1 000 lm. Generally speaking, the source of light emits a larger flux. Thus, the corresponding luminous intensity values are calculated by a simple ratio.

When a lamp is housed in a reflector, its flux is distorted, producing a volume with a marked shape defined by the characteristics of the reflector. Therefore, distribution curves vary according to different planes. The two following figures show two examples where distribution curves for two reflectors are represented. Fig.10 reflector is symmetric and has identical curves for any of the meridional planes. This is the reason why a sole curve is enough for its photometric identification. Fig. 11 reflector is asymmetric and each plane has a different curve. All planes must be known.

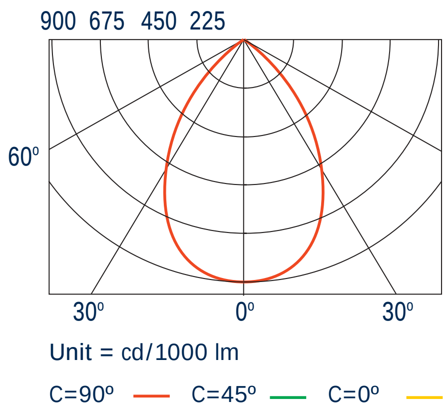


Figure 10. Symmetric photometric distribution curve.

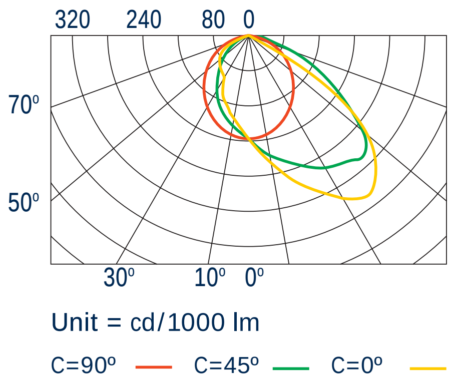


Figure 11. Asymmetric photometric distribution curve.

Another method to represent luminous flux distribution is the *isocandela curve* diagram (Fig. 12). According to this diagram, luminaires are supposed to be in the center of a sphere where exterior surface points with the same intensity are linked (isocandela curves). Generally, luminaires have, at least, one symmetric plane. This is the reason why they are only represented in a hemisphere.

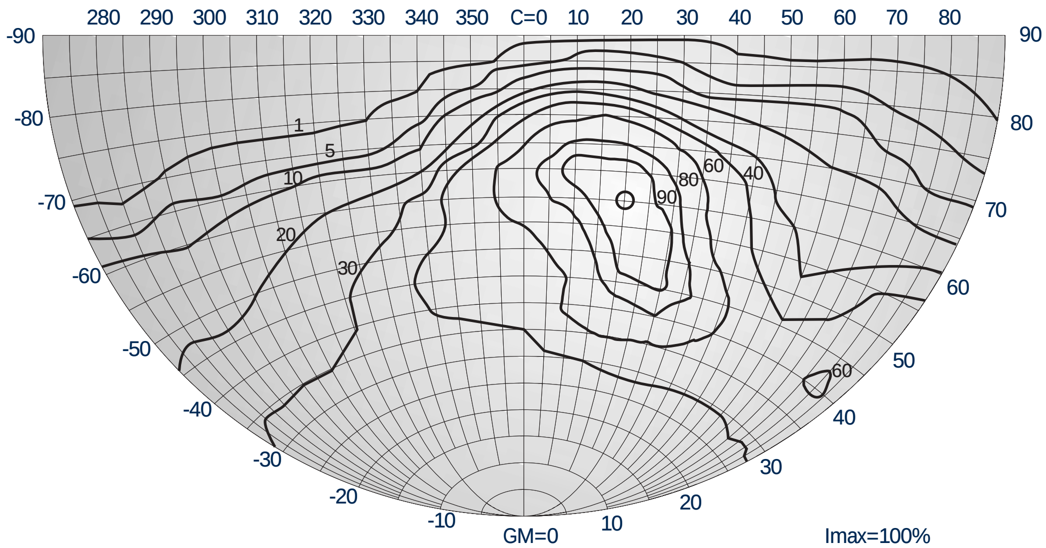


Figure 12. Isocandela curves.

This representation is very comprehensive. However, more experience is needed to interpret it.

The flux emitted by a source of light provides surface lighting (illuminance) whose values are measured in lux. If those values are projected on the same plane and a line links the ones with the same value, isolux curves are formed (Fig. 13).

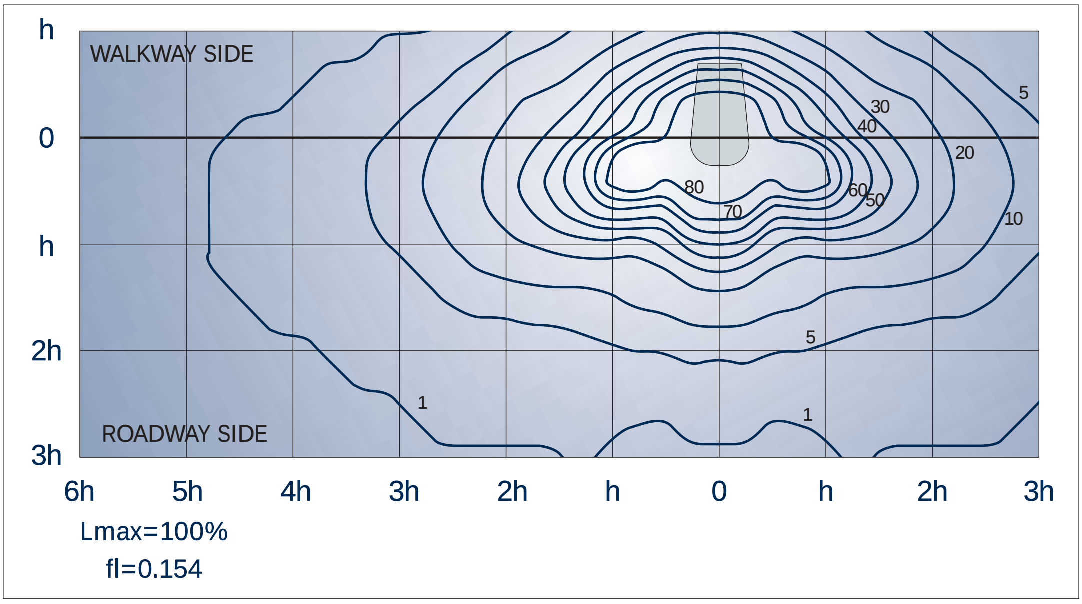


Figure 13. Isolux curves.

Finally, luminance depends on the luminous flux reflected by a surface in the observer's direction. Values are measured in candelas per square metre (cd/m^2) and are represented by *isoluminance curves* (Fig. 14).

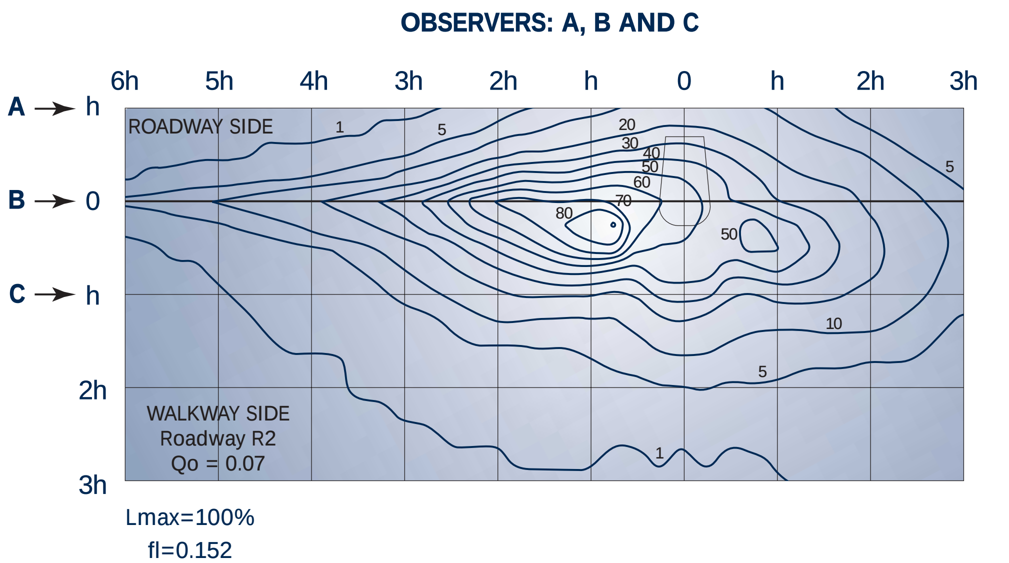


Figure 14. Isoluminance curves.

5.8. Luminous measurement summary chart

Measurement	Symbol	Unit	Ratio
Luminous flux	Φ	Lumen (lm)	$\Phi = I \cdot \omega$
Luminous efficacy	ε	Lumen per watt (lm/W)	$\varepsilon = \frac{\Phi}{P}$
Luminous output	$\mathbf{Q}$	Lumen per hour (lm · h)	$\mathbf{Q} = \Phi \cdot t$
Luminous intensity	I	Candela (cd) (cd = lm/sr)	$I = \frac{\Phi}{\omega}$
Illuminance	E	Lux (lx) (lx = lm/m^2)	$E = \frac{\Phi}{S}$
Luminance	L	Nit = cd/ m^2 Stilb = cd/cm^2	$L = \frac{I}{S \cdot \cos\beta}$
Utilization coefficient	η	%	$\eta = \frac{\Phi}{\Phi_e}$
Reflectance	ρ	%	$\rho = \frac{\Phi_r}{\Phi}$
Absorptance	α	%	$\alpha = \frac{\Phi_a}{\Phi}$
Transmittance	τ	%	$\tau = \frac{\Phi_t}{\Phi}$
Average uniformity factor	U_m	%	$U_m = \frac{E_{min}}{E_{med}}$
Extreme uniformity factor	U_e	%	$U_e = \frac{E_{min}}{E_{max}}$
Longitudinal luminance uniformity	U_L	%	$U_L = \frac{L_{longitudinal\ min}}{L_{longitudinal\ max}}$
Overall luminance uniformity	U_0	%	$U_0 = \frac{L_{min}}{L_{med}}$
Maintenance factor	F_m	%	$F_m = F_{pl} \cdot F_{dl} \cdot F_t \cdot F_e \cdot F_c$

Chart 1. Luminous measurement summary