21

Lighting

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21.1 Light and vision

Light is electromagnetic radiation, i.e., it has electric and magnetic fields, mutually at right angles and varying sinusoidally as shown in *Figure 21.1*. It is capable of causing a visual sensation in the eye of an observer. It is measured in terms of its ability to produce such a sensation.

The *spectral range* of visible radiation is not well defined, and can vary with the observer and with conditions. The lower limit is generally taken to be 380–400 nm (deep-blue radiation) and the upper limit 760–780 nm (deep-red radiation).

The human eye is not equally sensitive to all wavelengths, as shown in *Figure 21.2*. For normal daylight vision, referred to as *photopic vision*, the eye has a peak sensitivity at 555 nanometres (nm). The eye contains two distinct types of light-sensitive receptors referred to as *rods* and *cones*. The cones are responsible for colour vision whilst the rods operate in dark conditions.

At low levels of illumination the more sensitive rods begin to take over, and the resultant image appears less brightly coloured. Furthermore, the peak sensitivity shifts towards the blue/green region of the spectrum. This condition is known as *mesopic* vision.

At still lower levels vision is almost entirely by rod receptors and the eye is said to be dark-adapted. In this state, known as *scotopic* vision, the sensation is entirely in black and white and the peak sensitivity has moved to 505 nm.

The Commission Internationale de l'Eclairage (CIE) has defined an agreed response curve for the photopically adapted eye, known as the *spectral luminous efficacy* or $V(\lambda)$ function. Luminous flux, which is the rate of flow of light, is radiant power weighted according to its ability to produce a visual sensation by the $V(\lambda)$ function.

The luminous flux emitted by a source of light will vary with direction of emission. The rate of change of luminous flux with solid angle is termed the *luminous intensity*.

Illumination is the process whereby luminous flux is incident upon a solid surface and the corresponding quantity (flux density per unit area) is the *illuminance*.

Light striking a surface can be reflected, transmitted or absorbed according to the nature of the surface, and the fractions of the incident luminous flux thus affected are termed the reflectance, transmittance or absorptance, respectively.

21.2 Quantities and units

Each quantity has a quantity symbol (e.g. I for luminous intensity) and a unit symbol (e.g. cd for candela) to indicate its unit of measurement.

Luminous flux, Φ; lumen (lm) The rate of flow of luminous energy. A quantity derived from radiant flux by evaluating it according to its ability to produce visual sensation. Unless otherwise stated, luminous flux relates to photopic vision as defined by the $V(\lambda)$ function of spectral luminous efficacy.

If K_m is the maximum spectral luminous efficacy (about 680 lm . W^{-1} at a wavelength of 555 nm), then the luminous flux Φ (in lm) is related to the spectral power distribution $P(\lambda)$ at wavelength λ by

$$\Phi = K_m \int P(\lambda) \cdot V(\lambda) \cdot d\lambda$$

Luminous efficacy (of a source), η; lumens per watt (lm . W^{-1}) The quotient of the luminous flux emitted by a source to the input power. It should be noted that for discharge lamps the luminous efficacy may be quoted either for the lamp itself or for the lamp with appropriate control gear. The latter figure will be lower.

Luminous intensity, I; candela (cd) The quotient of the luminous flux $\delta\Phi$ leaving the source, propagated in an element of solid angle containing the given direction, by the element of solid angle $\delta\omega$ (see *Figure 21.3*).

$$I = d\Phi / d\omega$$

Illuminance, E; lux (lx) or lumens per metre^2 (lm . m^{-2}) The incident luminous flux density at a point on a surface. The quotient of the luminous flux incident on an element of surface, by the area of that element. Referring to *Figure 21.3*,

$$E = \delta\Phi / \delta A$$

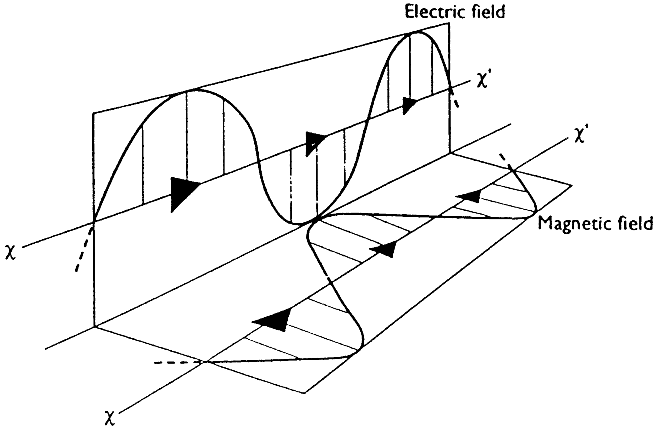


Figure 21.1 Electric field and magnetic field mutually at right angles. Electric field and magnetic field have same axis x–x′ but are shown separately for clarity only

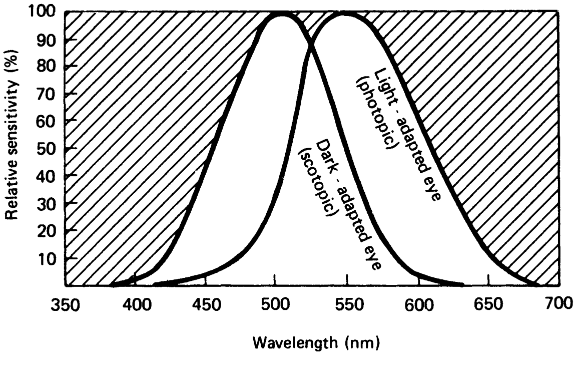


Figure 21.2 The relative spectral sensitivity of the human eye

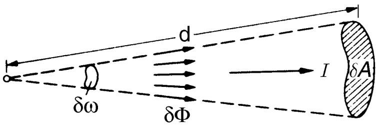


Figure 21.3 Luminous intensity and illumination

Note: the term *illuminance* is used for the quantity, while the term *illumination* describes the physical process.

Luminance, L; candela per metre^2 (cd m^{-2}) The luminous intensity in a given direction of a surface element, per unit projected area of that element.

Luminance is a physical measure of brightness, but it should be noted that an observer's assessment of the brightness of an object is subjective, unlike luminance which is the objective physical measure. It will depend upon the level of adaptation and other factors. For example, the luminance of a car headlight during the day and at night would be approximately the same, but the apparent brightness during the day would be significantly less.

21.3 Photometric concepts

Inverse square law The illuminance E at a point on a surface produced by light from a *point* source varies inversely with the square of the distance d from the source, and is proportional to the luminous intensity I towards that point. Referring to *Figure 21.3*, the illuminance is given by

$$E = I/d^2.$$

Cosine law The illuminance on a surface is proportional to the cosine of the angle θ between the directions of the incident light and the normal to the surface. This is due to the reduction of projected area as the angle of incidence increases from zero (normal incidence) to 90°. For a point source at distance d, the illuminance for angle θ is

$$E = E_0 \cos\theta = I\cos\theta/d^2$$

where E_0 is the illuminance for normal incidence, $\theta = 0$. With the working surface horizontal and the source mounted a distance h above the surface, the illuminance on the working surface is

$$E = I\cos^3\theta/h^2$$

involving θ as the only variable.

Reflection Light falling on a surface may undergo *direct* or *diffuse* reflection. Direct reflection is specular, as by a mirror. Diffuse reflection may be *uniform* or *preferential*: in the former the luminance is the same in all available directions; in the latter there are maxima in certain directions (see *Figure 21.4*). Direct and diffuse reflection may occur together as *mixed* or *spread* reflection.

Examples of reflecting surfaces are: direct (mirror glass, chromium plate); uniform diffuse (blotting paper); preferential diffuse (anodised aluminium, metallic paint).

Reflectance, R The ratio between the reflected luminous flux and the incident luminous flux.

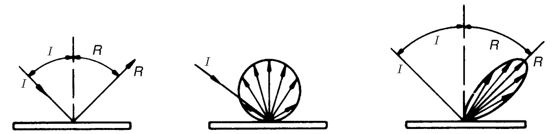
Transmission Light falling on a translucent surface undergoes partial transmission (*Figure 21.5*). The transmission may be *direct*, as through clear plate glass; *diffuse*, as through flashed opal glass; or *preferential*, as through frosted glass.

Transmittance, T The ratio between the transmitted luminous flux and the incident luminous flux.

Absorption That proportion of light flux falling on a surface which is neither reflected nor transmitted is *absorbed* and, normally, converted into heat.

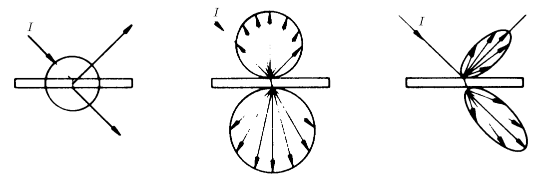
Refraction While a light ray is travelling through air, its path is a straight line. When the ray passes from air to glass (or any transparent material, e.g. clear plastics, diamonds, etc.), the ray is, in general, bent at the surface of separation. The path of the ray after bending or refraction from air to glass is always more nearly perpendicular to the bounding surface than is that of the incident ray. The degree to which the ray is bent depends on the type of glass or transparent material, the angle of incidence of the ray and also the colour of the light.

Should the ray, while in the glass, strike another bounding surface, it may again be refracted. In this case the



DIRECT REFLECTION DIFFUSED REFLECTION SPREAD REFLECTION

Figure 21.4 Reflection



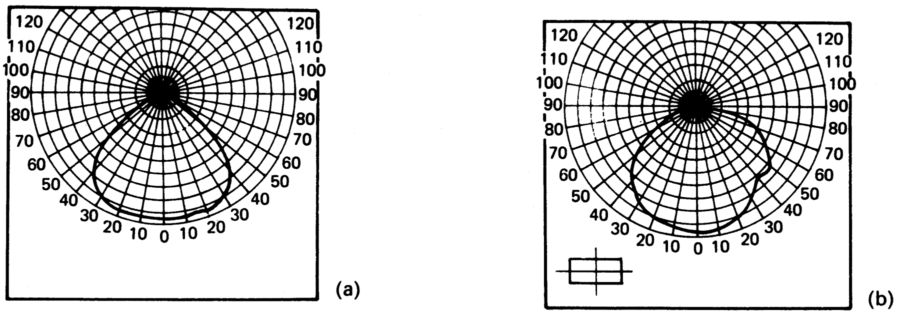
DIRECT TRANSMISSION DIFFUSED TRANSMISSION SPREAD TRANSMISSION

Figure 21.5 Transmission with partial reflection refracted ray may be more nearly parallel to the bounding surface than is the incident ray. If the light ray strikes the bounding surface at any angle above a certain limit (the *critical* angle), it will not be refracted but will be totally reflected.

Both refraction and total internal reflection are used in the design of lighting units, the prismatic types of reflector being typical examples.

Polar intensity distributions Utilising the inverse-square and cosine laws, it is possible to calculate the direct illuminance at a point from a single luminaire, or an installation, using the 'point-by-point' method. The effect of interreflected light is not included, as the calculations are too complex to warrant it.

Figure 21.6 shows the intensity distributions for two different interior luminaires: (*a*) is for a luminaire with a luminous intensity distribution symmetrical about a vertical axis, and (*b*) is for a non-symmetrical luminaire with a luminous intensity distribution symmetrical about two orthogonal vertical planes. These are typical of discharge and fluorescent luminaires, respectively.



Luminous intensity (cd per 1000 lm)	
Angle (deg)	Mean vertical intensity (cd)
0	234
5	234
10	235
15	236
20	234
25	232
30	230
35	222
40	205
45	180
50	137
55	95
60	66
65	46
70	30
75	19
80	13
85	11
90	9
95	9
100	9
105	10
110	11
115	13
120	15
125	18
130	22
135	28
140	32
145	35
150	34
155	30
160	26
165	20
170	14
175	7
180	4

	Luminous intensity (cd per 1000 lm)	
Angle (deg)	Transverse plane (T)	Axial plane (A)
0	232	232
5	232	230
10	231	228
15	231	224
20	228	217
25	224	208
30	220	199
35	211	187
40	192	174
45	168	199
50	141	187
55	113	174
60	86	159
65	58	142
70	33	124
75	19	106
80	12	85
85	7	67
90	1	46
95	2	28
100	5	11
105	7	1
110	8	2
115	9	2
120	11	2
125	12	3
130	13	4
135	14	5
140	14	6
145	15	7
150	16	8
155	16	9
160	16	10
165	15	10
170	13	11
175	12	11
180	12	12

Figure 21.6 Luminous intensity distributions for: (a) symmetric luminaires and (b) non-symmetric luminaires

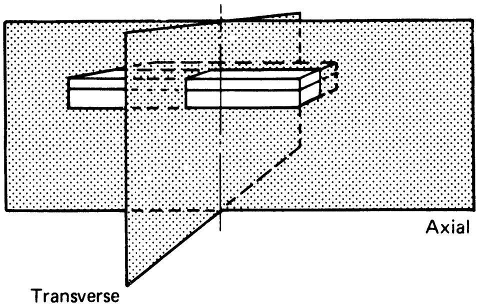


Figure 21.7 The transverse and axial planes in which the transverse and axial polar curves are measured

For symmetric luminaires, only one average intensity distribution is normally given, and this can be presented graphically on polar co-ordinates or in tabular form (which is easier to use). For non-symmetrical luminaires two or more distributions are given. The principal ones are the *axial* and *transverse* distributions, which lie in vertical planes down the axis of the luminaire, and at right angles thereto, respectively (*Figure 21.7*).

Many luminaires can accommodate various lamp types without affecting the shape of the intensity distribution. For this reason it is a common practice to quote intensities in candelas per 1000 lamp lumens (cd . klm^{-1}) rather than in candelas. This permits easy scaling of the data according to the luminous output of the lamps.

For streetlighting and floodlighting luminaires, the main distributions are usually insufficient, and contours of equal intensity (isocandela) are normally published on a convenient Cartesian grid system, as shown in *Figure 21.8*.

Isolux diagrams A convenient way of plotting the illuminance produced by single luminaires or complete installations is by contours of equal illuminance, or isolux contours. Isolux diagrams are frequently used to depict the performance of non-symmetrical luminaires such as 'wall-washers', and are now often used when the calculations are done by computer. *Figure 21.9* shows a typical isolux diagram for a reflector luminaire at a particular mounting height.

21.4 Lighting design terminology

Light output ratio (LOR) The ratio between the light output of the luminaire measured under specified practical conditions and the sum of the light outputs of individual lamps operating outside the luminaire under reference conditions.

Photometric centre The point in a luminaire or lamp from which the inverse square law operates most closely in the direction of maximum intensity.

Upward (downward) flux fraction (UFF (DFF)) The fraction of the total luminous flux of a luminaire emitted above (below) the horizontal plane containing the

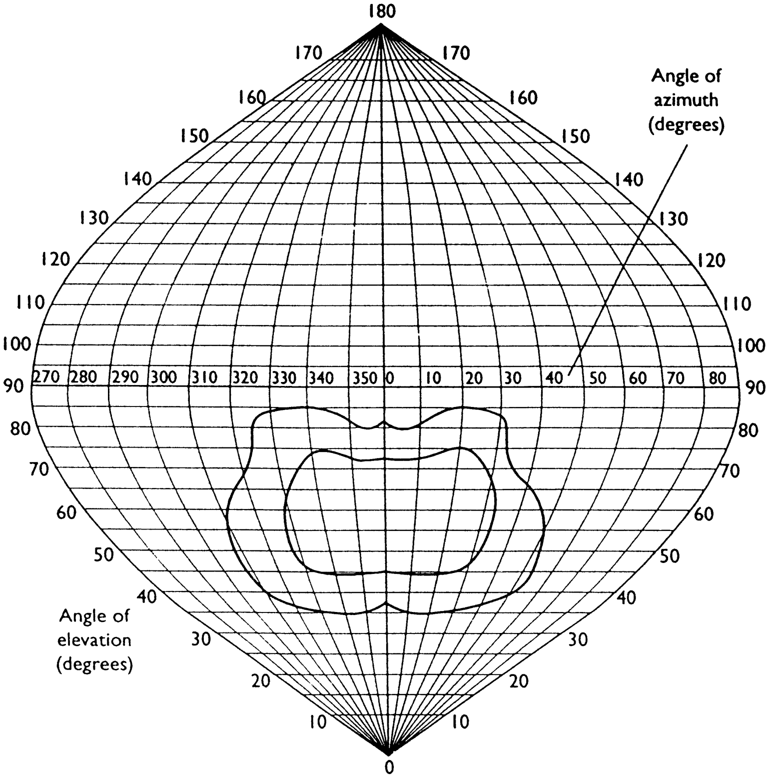


Figure 21.8 Typical isocandela diagram. Figures on contour lines represent luminous intensities in candela per 1000 lamp lumens

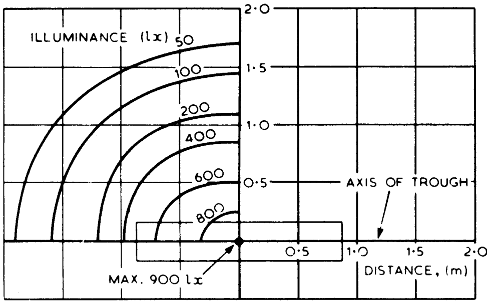


Figure 21.9 Isolux diagram for a 1.8 m long trough reflector luminaire

photometric centre of the luminaire. Also known as upper (lower) flux fraction.

Upward (downward) light output ratio (ULOR (DLOR)) The product of the light output ratio of a luminaire and the upward (downward) flux fraction.

Symmetric luminaire A luminaire with a light distribution nominally rotationally symmetrical about the vertical axis passing through the photometric centre.

Non-symmetric luminaire A luminaire with a light distribution nominally symmetrical only about two mutually perpendicular planes passing through the photometric centre. Where such a luminaire is linear, the vertical plane of symmetry normal to the long axis is designated the *transverse* plane, and the vertical plane passing through the long axis is designated the *axial* plane (see *Figure 21.7*). The vertical distributions taken in these planes are the transverse and axial distributions, respectively.

Working plane The horizontal, vertical or inclined plane in which the visual task lies.

Reference surface The surface of interest over which the illuminance is to be calculated. A reference surface need not contain the visual task.

Horizontal reference plane A horizontal reference surface. This is usually assumed to be 0.85 m above the floor and to correspond with the horizontal working plane. The horizontal reference plane is also the mouth of the floor cavity.

Plane of luminaires The horizontal plane which passes through the photometric centres of the luminaires in an installation. This is also the mouth of the ceiling cavity.

Floor cavity The cavity below the horizontal reference plane in a room (see *Figure 21.10*). The horizontal reference plane and the floor cavity may be designated by the reference letter F.

Walls The vertical surfaces of a room between the plane of the luminaires and the horizontal reference plane (see *Figure 21.10*). The walls may be designated by the reference letter W.

Ceiling cavity The cavity above the plane of the luminaires in a room (see *Figure 21.10*). The luminaire plane and the ceiling cavity may be designated by the reference letter C.

Distribution factor, DF(S) The distribution factor for a surface S is the ratio between the direct flux received by the surface S and the total lamp flux of the installation. DF(F), DF(W) and DF(C) are the distribution factors for the floor cavity, walls and ceiling cavity, respectively, treated as notional surfaces.

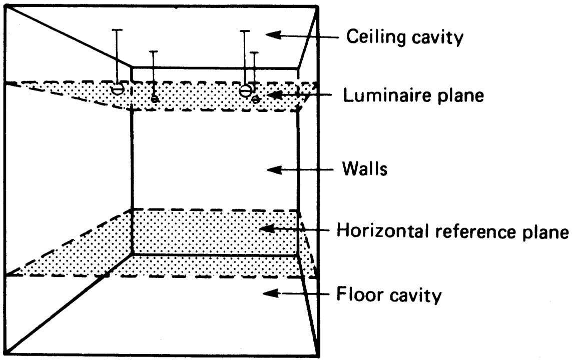


Figure 21.10 Ceiling cavity, walls and floor cavity

Utilisation factor, UF(S) The utilisation factor for a surface S is the ratio between the total flux received by the surface S (directly and by inter-reflection) and the total lamp flux of the installation. UF(F), UF(W) and UF(C) are the utilisation factors for the floor cavity, walls and ceiling cavity, respectively, treated as notional surfaces.

Direct ratio, DR The proportion of the total downward flux from a conventional installation of luminaires that is directly incident on the horizontal reference plane. The direct ratio is equal to DF(F) divided by the DLOR of the luminaires.

Zone factor The solid angle subtended at the photometric centre of a lamp or luminaire by the boundary of a zone. The zonal flux is obtained by multiplying the intensity of the lamp or luminaire, averaged over the zone, by the zone factor.

Room index, RI Twice the plan area of a room divided by the wall area (as defined above). The room is taken to have parallel floor and ceiling, and walls at right angles to these surfaces. From any point in the room all of the surfaces in the room should be visible.

Spacing/height ratio, SHR The ratio between the spacing in a stated direction between photometric centres of adjacent luminaires and their height above the horizontal reference plane. It is assumed that the luminaires are in a regular square array unless stated otherwise.

Maximum spacing/height ratio, SHR MAX The SHR for a square array of luminaires that gives a ratio between minimum and maximum direct illuminance of 0.7 over the central region between the four innermost luminaires.

Maximum transverse spacing/height ratio, SHR MAX TR The SHR in the transverse plane for continuous lines of luminaires that gives a ratio between minimum and maximum direct illuminance of 0.7 over the central region between the two inner rows.

Nominal spacing/height ratio, SHR NOM The highest value of SHR in the series 0.5, 0.75, 1.0, etc., that is not greater than SHR MAX. Utilisation factor tables are normally calculated at a spacing/height ratio of SHR NOM.

Maintenance factor, *MF* The ratio between the illuminance provided by an installation in the average condition of dirtiness expected in service and the illuminance from the same installation when clean. It is always less than unity.

Uniformity The ratio between the minimum and average illuminance over a given area. For interior lighting it should be not less than 0.8 over the task area. This requirement can be satisfied by ensuring that the spacing/height ratio of an installation does not exceed SHR MAX.

Daylight factor, *DF* The ratio between the illumination measured on a horizontal plane at a given point inside a building and that due to an unobstructed hemisphere of sky. Light reflected from interior and exterior surfaces is included in the illumination at the point, but direct sunlight is excluded.

21.5 Lamps

Light can be produced from electrical energy in a number of ways, of which the following are the most important.

(1) *Thermoluminescence*, or the production of light from heat. This is the way light is produced from a filament lamp, in which the filament is incandescent.
(2) *Electric discharge*, or the production of light from the passage of electricity through a gas or vapour. The atoms of the gas are excited by the passage of an electric current to produce light and/or ultraviolet energy.
(3) *Fluorescence*, a two-step production of light which starts with ultraviolet radiation emitted from a discharge; the energy is then converted to visible light by a phosphor coating within the lamp.

21.5.1 Incandescent filament lamps

Thermoluminescence is the emission of light by means of a heated filament. The term is normally synonymous with the tungsten filament lamp in its various forms. The most general form is the general lighting service (GLS) lamp (*Figure 21.11*). Light produced from a hot wire increases as the temperature of the wire is raised. It also changes from a predominantly red colour at low temperature to a white which approaches daylight as the temperature is increased.

Of the electrical energy supplied to an incandescent lamp filament, by far the greatest proportion is dissipated as heat, and only a small quantity as visible light (about 95% heat and 5% light) (see *Figure 21.12*). Because the quantity of visible light emitted depends upon the filament temperature, the higher the filament temperature the greater will be the visible light output in lumens per watt of electric power input. Thus, for an incandescent filament, a material is needed that not only has a high melting point, but is also strong and ductile so that it can be formed into wire. At present, tungsten metal is the material nearest to this ideal.

The colour temperature of a normal GLS filament lamp is typically between 2800 K and 3000 K. At the extremely high temperature of the filament, tungsten tends to evaporate. This leads to the familiar blackening of an incandescent lamp envelope. The evaporation of the tungsten filament can be reduced by filling the lamp envelope with a suitable gas that does not chemically attack the filament. Suitable gases are hydrogen, nitrogen, and the inert gases argon, neon, helium, krypton and xenon. However, gases also cool the filament by conducting heat away from it, and they decrease lamp efficiency. The gas used must therefore be carefully chosen. It should adequately suppress tungsten evaporation without overcooling the filament. In addition, it should not readily pass an electric current, for otherwise arcing may occur which would destroy the lamp.

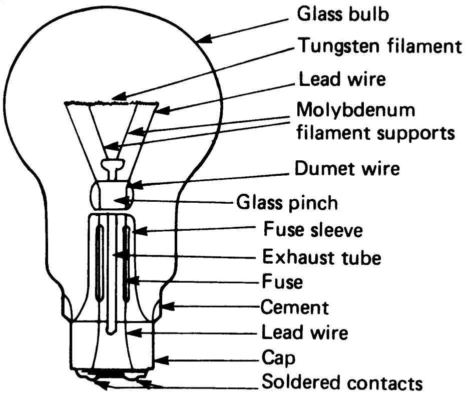


Figure 21.11 Construction of a GLS lamp

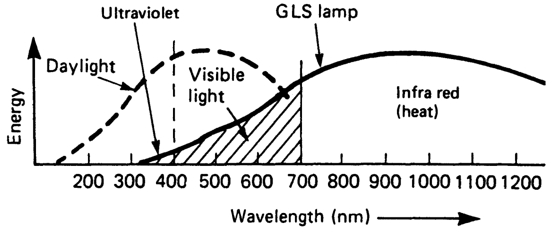


Figure 21.12 Spectral power distribution of daylight and a GLS lamp

Argon and nitrogen are the gases most commonly used. Nitrogen will minimise the risk of arcing, but will absorb more heat than argon. Argon is used by itself in general service lamps. A mixture of the two gases is used in incandescent lamps where the tendency for arcing is more likely, such as in projector lamps. In this case the amount of nitrogen present is kept very small—as little as 5%—in order to obtain optimum lamp efficiency.

Not all incandescent lamps benefit from gas filling. Mains voltage 15 W and 25 W lamps are mainly of the vacuum type, whereas lamps of 40 W and above are normally gas filled.

In general service lamps at least one lead is fused to prevent the envelope shattering should an arc occur. Modern fuses are encapsulated in a glass sleeve filled with small glass balls.

21.5.1.1 Coiled and coiled-coil filaments

If a filament is in the form of an isolated straight wire, gas can circulate freely round it. Filament temperature is thus decreased by convection currents, and has to be raised by increasing the electrical power input.

Coiling the wire reduces the cooling effect, the outer surface of the helix alone being cooled by the gas. Further coiling (coiled-coil filament) again reduces the effect of the gas cooling and results in further increase in lamp efficiency of up to 15%.

21.5.1.2 Glass envelopes

Clear-glass lamp envelopes have smooth surfaces and absorb the smallest possible amount of the light passing through them. The high temperature of the filament results in a high brightness which the envelope does not modify.

Early attempts to reduce glare from an unobscured filament used envelopes externally frosted. These were difficult to keep clean. The drawback is obviated in the modern *pearl* envelope by etching the inside surface instead. The light source appears to be increased in size and to have a larger surface area. The loss of light is negligible.

With the greatly increased illumination levels of modern lighting techniques, a further degree of diffusion is called for. This has been achieved by coating the inside of the envelope with a very finely divided white powder, such as silica or titania. In such lamps the lighted filament is not apparent. The luminous efficiency of the silica coated lamp is about 90% of that of a corresponding clear lamp of equal power rating. Silica coated lamps have a more attractive unlit appearance than either clear or pearl lamps.

In a coloured incandescent lamp the envelope is coated either internally or externally with a filter. All coloured incandescent lamps operate at reduced efficiency. In view of the low proportion of blue light in the spectrum, the efficiency of lamps of this colour is particularly low, as more than 90% of the light is filtered out. It is not possible to obtain a bright saturated blue colour.

21.5.1.3 Decorative and special-purpose lamps

The incandescent filament lamp in its simplest form is purely a functional light source, but the fact that an integral part of the lamp has a glass envelope enables the manufacturer to adapt this envelope to give some aesthetic appeal. The commonest form is the candle lamp, with glass clear, white or frosted. Other lamps have been marketed which combine the role of light source and decorative luminaire by virtue of their envelope shape. They are usually of larger dimensions than conventional lamps. Apart from their attractive shapes, they are made with silica coatings, coloured lacquer coatings and crown silvered tops, and are therefore rather more efficient as light-producing units than a combination of lamp and separate diffuser.

To cater for locations where vibration and shock are unavoidable, special *rough service* lamps are produced which combine filament wire modifications with the inclusion of an increased number of intermediate filament supports.

To provide directional beam control a further range of special-purpose lamps is made with blown or pressed paraboloidal envelope shapes coated with an aluminium reflector film. The filament is accurately placed at the focus of the reflector to provide the directional beam. More accurate beam control is provided by the pressed glass versions (PAR lamps).

In some lamps dichroic reflectors are employed. These reflect visible light but transmit infrared radiation. This permits the lamp to have a cooler beam, since the heat radiation is not focused. However, these lamps can be used only in luminaires able to dissipate the extra heat transmitted by the reflector. Dichroic coatings are widely used in film projector lamps with integral reflectors, to prevent excessive temperature at the film gate. *Figure 21.13* shows the concept of the dichroic lamp

The efficacy of an incandescent lamp is related to the quantity of visible light emitted per unit of electrical power input. Thus, a 100 W incandescent lamp having a total light output of 1200 lm has an efficacy of $1200/100 = 412\,\mathrm{lm\,.\,W^{-1}}$.

A higher filament temperature increases lamp efficacy, but the temperature of a tungsten filament cannot be increased indefinitely, as it will melt catastrophically if the lamp efficacy approaches $40\,\mathrm{lm\,.\,W^{-1}}$.

At high filament temperatures tungsten evaporation—even though it is reduced by gas filling—is more rapid and leads to a shorter lamp life. Thus, the more efficient an incandescent lamp is the shorter is its life.

Variations in supply voltage vary filament temperature, which, in turn, increases or decreases lamp life. *Figure 21.14* shows how the lamp efficiency, life, light output and input power vary with supply voltage. For example, if a lamp is under-run by 5% below its rated voltage, its life will be nearly doubled (190% of rated 1000-h life) but the lamp power would be reduced to around 92% of the rating and the light output to less than 85% of the normal lumen output.

21.5.1.4 Tungsten halogen lamps

If the envelope of a tungsten lamp is made of quartz instead of glass, it can be much smaller, because quartz can operate safely at a higher temperature. As with a glass lamp, tungsten evaporated from the filament will deposit on the quartz envelope, causing it to blacken. However, if a small quantity of one of the halogen elements e.g. iodine is introduced into the lamp, and if the temperature of the quartz envelope is above 250°C, the iodine combines with the tungsten on the inner face of the quartz to form tungsten iodide, a vapour.

When the tungsten iodide approaches the much hotter filament, it decomposes; the tungsten is deposited on the filament and the iodine is released, to perform its cleaning cycle again (see *Figure 21.15*).

Unfortunately, the tungsten is not necessarily redeposited on those parts of the filament from which it originally

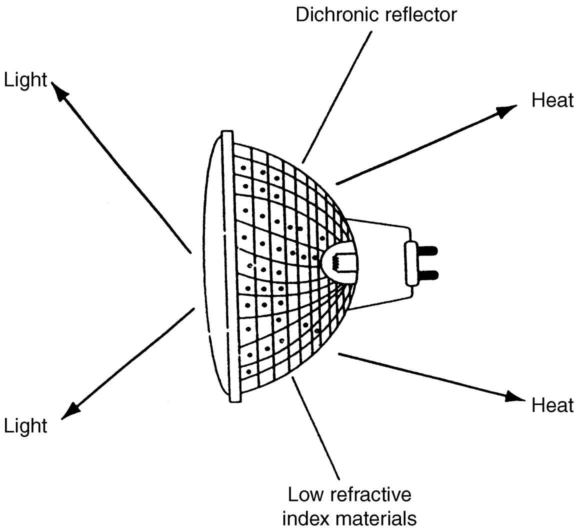


Figure 21.13 Dichroic reflector lamp

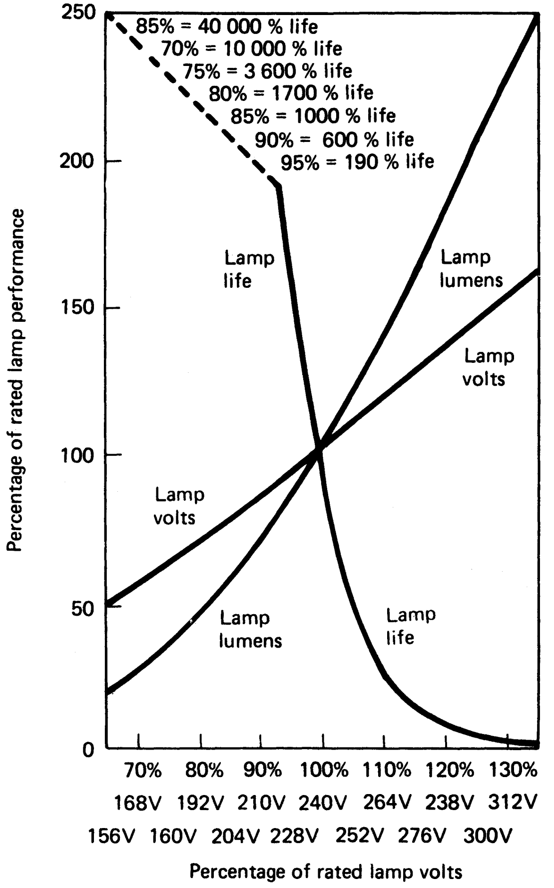


Figure 21.14 Typical effect of voltage on incandescent filament lamps

evaporated. Even so, substantial improvements in life and/or higher filament operating temperatures can be achieved, giving higher lumen outputs compared with the equivalent GLS lamp.

The increase in life is mainly due to the increased gas pressure, which can be employed in a tungsten halogen lamp to reduce filament evaporation. This, in turn, is only possible because a small outer envelope can be used without risk of lamp envelope blackening.

Tungsten halogen lamps give greater life and greater efficiency than their incandescent counterparts. For this reason they are widely used in floodlighting, photographic lighting, display lighting and automobile lighting. A typical tungsten halogen lamp will provide about 50% greater light output and about twice the life of a conventional tungsten lamp of an equivalent wattage.

Tungsten halogen lamps come in several common forms. Small capsule lamps with bi-pin lamp holders are used in spotlights and for similar applications needing good optical control and a small optical light source. The same type of lamp, but optimised to give shorter life and much higher light output, is used in photographic projectors and similar applications.

Small capsule lamps can also be built into glass or metal reflectors which form part of the lamp. These small diameter, high performance lamps are now widely used for display lighting. With such lamps the wattage, lamp diameter (typically 20 mm or 50 mm) and beam angle are normally specified. One advantage of this type of mirror lamp is that the reflector can be manufactured from glass with dichroic coatings. Such reflectors are designed to reflect light into the beam but not the heat. Lamps of this type are popular for display lighting because they direct very little heat onto the merchandise being displayed.

The third type of tungsten halogen lamp is the linear lamp. These are used for applications where a wide beam angle is required together with a high wattage. Such lamps are used for floodlights where low capital cost or instant white light is required. The lamps have an electrical contact at each end and vary in length according to wattage.

Tungsten halogen lamps are designed to operate with an envelope temperature of 250°C to 350°C. The design of the luminaire and the location of the equipment should ensure that people cannot touch the lamp and burn themselves. Similarly, flammable objects should be kept away from the lamp.

In a conventional tungsten lamp, although some ultraviolet radiation is produced, most of it is severely attenuated by the glass outer envelope. In a tungsten halogen lamp, the higher operating temperature and quartz envelope produces a greater ultraviolet content. Although ultraviolet radiation is present in sunlight and daylight, steps should be taken to limit human exposure where high lighting levels are involved.

Both of the above problems can be eliminated if either the lamp or the luminaire is fitted with an ultraviolet radiation absorbing front glass.

The quartz envelope of a tungsten halogen lamp should not come into contact with the human skin e.g. fingers. The greases and acids, which are present on the surface of the skin, will attack the quartz. This will subsequently produce blistering of the envelope leading to premature lamp failure.

21.5.2 Discharge lamps

21.5.2.1 Principle

A discharge lamp consists essentially of a tube of glass, quartz or other suitable material, containing a gas and, in most cases, a metal vapour. The passage of an electric current through this gas/vapour produces light or ultraviolet radiation. Most practical discharge lamps (excluding those used for coloured signs) rely upon discharges in metallic vapours of either sodium or mercury, with an inert gas filling. The nature of the filling, the pressure developed and the current density determine the characteristic radiation produced by the arc. In most lamps the arc tube is enclosed within an outer glass or quartz jacket. This affords protection, can be used for phosphor or diffusing coatings, control of ultraviolet radiation emission and, by suitable gas filling, can control the thermal characteristics of the lamp.

All discharge lamps include some mechanism for the production of electrons from the electrodes within the lamp. The commonly used methods are thermionic emission and field emission, and in both cases emissive material such as barium oxide is often contained within the electrode to lower its work function and, hence, reduce energy loss.

When the lamp is put into circuit and an electric field is applied, the electrons begin to accelerate towards the positive electrode, and may collide with gas or metal atoms.

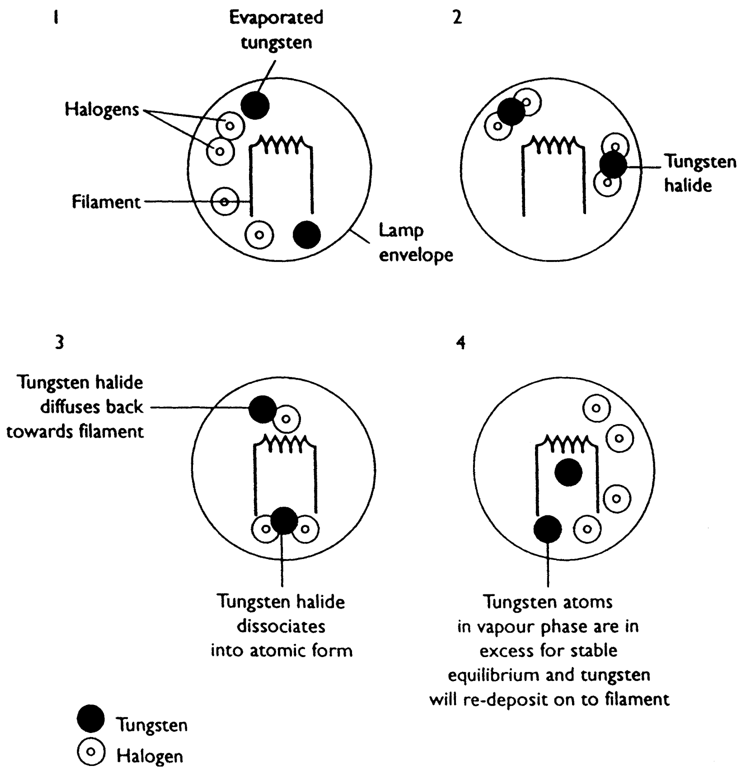


Figure 21.15 Tungsten halogen cycle

These collisions may be elastic, in which case the atom and electron only change their velocities, or inelastic, in which case the atom changes its state. In the latter case, if the kinetic energy of the electron is sufficient, the atom may become excited or ionised. Ionisation produces a second electron and a positive ion, which contribute to the lamp current and which may cause further collisions. Left unchecked, this process would avalanche, destroying the lamp. To prevent this catastrophe some form of electrical control device (such as an inductor) is used to limit the current. Excitation occurs when the electrons within the atom are raised to an energy state higher than normal (but not high enough to cause ionisation). This is not a stable condition, and the electrons fall back to their previous energy level, with a corresponding emission of electromagnetic radiation (which may be visible, ultraviolet or infrared).

In some lamp types, an inert gas is used to maintain the ionisation process, while it is the metal vapour which becomes excited. The vapour pressure in the lamp affects the starting and running characteristics, and the spectral composition of the emitted radiation.

In most lamps there is a run-up period, during which the metal is vaporised and the pressure increases to its operating condition. In some lamp types this may take 10–15 min. If, once the lamp is run-up, the supply is interrupted, then it will extinguish; and unless special circuits and suitable lamp construction are used, the pressure will be too high for the arc to restrike until the lamp has cooled.

Broadly, practical discharge lamps for lighting are either mercury vapour or sodium vapour lamps, at either high or low pressure.

21.5.2.2 Run-up efficiency

Smith devised a method of calculating the 'Run-up efficiency' of a discharge lamp (see *Lighting for Health and Safety*, Butterworth-Heinemann, ISBN 0-7506-4566-0).

Figure 21.16 shows the concept of 'run-up efficiency', which describes the efficiency with which a discharge lamp attains steady-state luminous output from a cold start. The diagram shows a typical locus of the instantaneous values of light output of a discharge lamp, with increasing time from switch-on from a cold start. Area 'A' represents the mathematical product of light output and elapsed time during the lamp 'run-up' period (measured in percentage-minutes). Area 'B' represents the mathematical product of the steady-state light output and time (also measured in percentage-minutes) over the same time duration as that taken for the lamp to run-up, i.e. the same time duration as that applying for area 'A'.

The run-up efficiency is then calculated from:

$$\text{Run-up efficiency} = \frac{\text{Area A}}{\text{Area B}} \times 100\%$$

21.5.2.3 Discharge lamp types

Discharge lamp types include low pressure mercury (fluorescent), induction, high pressure mercury vapour, mercury-blended, metal halide, low pressure sodium and high pressure sodium.

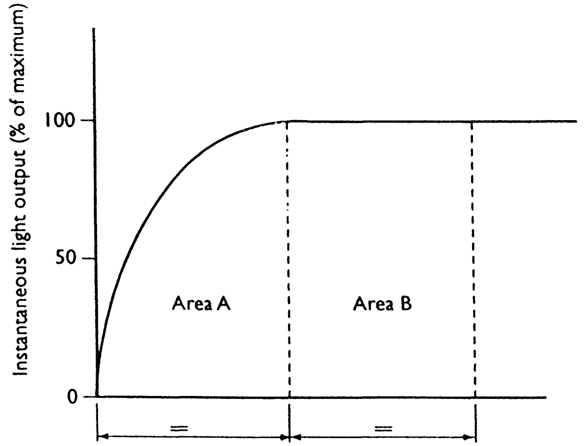


Figure 21.16 Concept of run-up efficiency

21.5.3 Mercury lamps

21.5.3.1 Low pressure mercury fluorescent lamps

Construction A typical mercury fluorescent tube consists of a glass tube, and up to 2400 mm long, filled with argon or krypton gas and containing a drop of liquid mercury. A diagram of the tube is shown in *Figure 21.17*. The interior surface of the tube is coated with a fluorescent powder, the phosphor, which converts the ultraviolet light produced by the discharge into visible light. At each end of the tube are electrodes which serve the dual purpose of cathode and anode, for generally these tubes are used on a.c. circuits.

The cathodes of a hot cathode fluorescent lamp consist of coiled-coil, triple-coiled or braided tungsten filaments, coated with a barium oxide thermionic emitter and held by nickel support wires. Cathode shields in the form of metal strips bent into an oval shape surround the cathodes in certain sizes of tube and are supported on a separate wire lead. These shields trap material given off by the cathodes during life and prevent black marks forming at the ends of the tube. The shields also reduce flicker which is sometimes noticeable at the ends of the tubes, and protect the more delicate cathodes by acting as anodes on alternate half periods. The bases of the electrode support wires are gripped in a glass pinch through which the lead wires pass, forming a vacuum-tight glass-to-metal seal.

The lead-in wires are welded to the pins of the bi-pin cap, which is itself sealed to the ends of the glass tube. Some tubes are still available with a BC cap, but the bi-pin cap is now British standard.

Principle An external control circuit is required, which causes a preheating current to flow through the electrodes. This causes electrons to be emitted by the emitter coating. Once these have been produced, the control circuit must apply an electric field across the length of the lamp to accelerate the electrons and strike the arc. Once struck, the arc must be stabilised by the control circuit.

Colliding electrons excite mercury atoms, and produce ultraviolet and visible radiation (about 60% of the energy consumed is converted to ultraviolet radiation). This radiation, when absorbed by the phosphor on the inside of the glass wall, is converted to visible light.

The colour and spectral composition of radiated light will depend upon the phosphors used. Lamps can be made with a 'white' appearance but with widely different efficacies or colour rendering properties.

Basic starter-switch circuit The basic starter-switch circuit is shown in *Figure 21.18*(*a*). The principle of operation is as follows:

(a) When the mains voltage is applied, a glow discharge is created across the bi-metal contacts inside the glow starter (enclosed in a small plastic canister). The contacts warm up and close, completing the starting circuit and allowing a current to flow from the 'L' terminal, through the current limiting inductor through the two tube cathode filaments and back to the 'N' mains terminal.

(b) Within a second or two, the cathode filaments are warm enough to emit electrons; a glow is seen from each end of the tube. At this stage, the starter-switch bi-metal contacts open (because the glow discharge, which caused them to heat and close, ceases when they touch, and they cool and open), and interrupt the preheat current flow. If an inductor (*choke*) ballast (coils of copper wire around a laminated iron core) is used the magnetic energy stored in the core collapses to produce a high-voltage pulse (600–1000 V) across the fluorescent tube sufficient to strike the arc and set up the electric discharge through the tube.

(c) Once the tube arc has been struck, the current through the tube gradually builds up. This means that the current through the inductor also increases. As this happens, the voltage across the inductor increases and the tube voltage falls. The inductor is so designed that when the tube and inductor current rise to a value determined by the inductor design setting, the circuit stabilises.

Electronic start circuit An improvement of the basic starter-switch circuit (*Figure 21.18*(*b*)) is the electronic start circuit. It is identical with the starter-switch circuits in all respects but one; the glow starter is replaced by an all electronic starter. In some cases it may be fitted into a conventional glow start canister, as a direct replacement, and in other more sophisticated luminaires it is a small encapsulated box.

The main advantages of this circuit are that it affords reliable starting, does not shorten tube life (a problem with

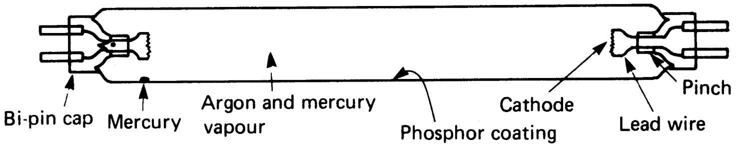


Figure 21.17 Low pressure mercury vapour fluorescent tube

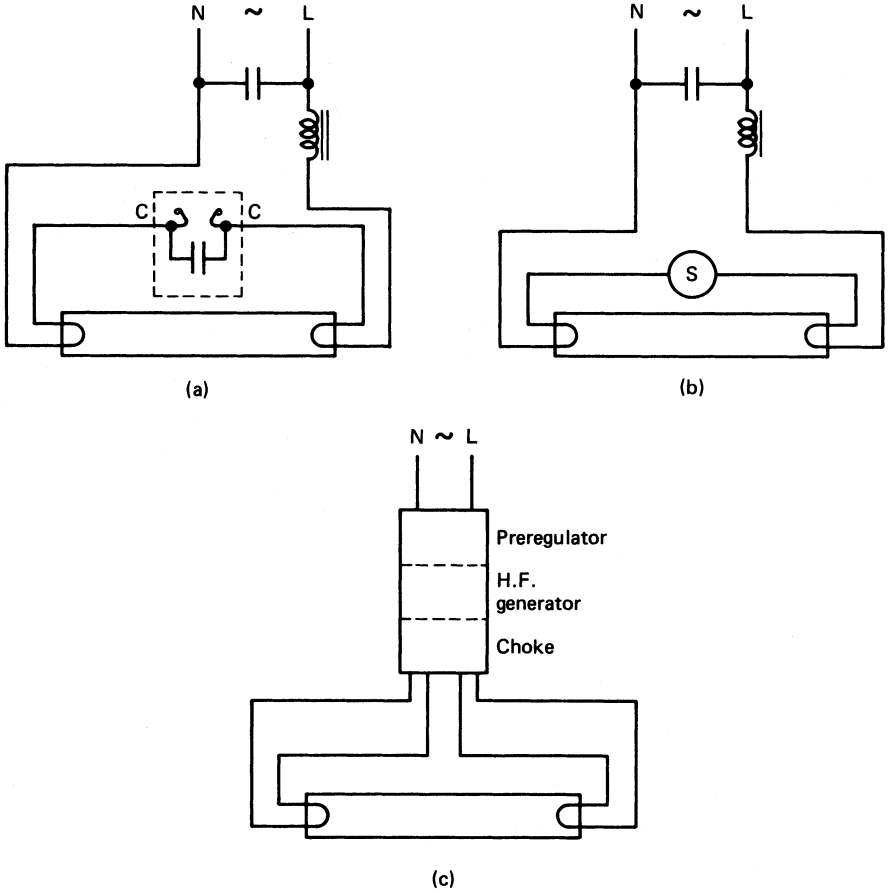


Figure 21.18 Starting methods: (a) glow starter; (b) electronic starter; (c) electronic control gear

glow switches at the end of their life) and will last the life of the luminaire without replacement. Some circuits also inhibit the start of faulty lamps after a number of unsuccessful attempts.

Low loss control gear The main power losses in the control gear are the result of heating and eddy current losses. In order to improve energy efficiency, thicker wire with lower resistance can be used in the ballast and the ballast can be made more cubic in shape. When this happens the power losses in the ballast are reduced but the ballast is more costly. Such ballasts are commonly referred to as 'low loss' and 'super low loss' according to their power dissipation. There is no definition of standard, low loss or super low loss; therefore comparisons must be based on measured losses.

It should be noted that, although they improve efficiency, such ballasts are more expensive, heavier and occupy a much larger and more awkward volume than conventional ballasts. This may cause problems by increasing the weight and bulk of the luminaires.

Electronic ballast Electronic ballasts offer several major advantages. They are lighter and replace several discrete components by one unit. They dramatically reduce the losses in the control gear, saving energy. Most designs provide a near-unity power factor, reducing the current drawn from the supply. The ballast also operates the lamp more efficiently, reducing the power losses within the lamp itself. Better starting will normally prolong lamp life. Better designs will operate over a wide range of supply voltage fluctuation.

Some designs can only be used with special lamps, but most will work with any standard lamp type from any manufacturer.

Electronic ballasts generate a high-frequency supply to the lamp (typically 30 kHz). At this frequency the normally bulky wire wound ballast can be made small and light. The ballast can be very efficient, but the generation of high frequency can give rise to conducted and radiated interference. Therefore, most circuits are in three parts. The first part of the circuit is designed to ensure that the supply form is not corrupted and that interference is not radiated. The second part of the circuit generates a high-frequency supply. The third part of the circuit uses the high-frequency supply through very small chokes to control the current and voltage to the lamp (*Figure 21.18*(*c*)).

Older 'hybrid' designs of electronic ballast use large iron core chokes in order to filter the supply waveform and prevent supply corruption. Such ballasts are normally heavier and bulkier than their conventional counterparts and do not offer the advantages of the fully electronic designs.

Not all ballasts generate true high frequency. Some simply chop the mains waveform at high frequency. Those which generate true high frequency have two other advantages. Firstly, at 30 kHz fluorescent lamps operate more efficiently. Typically the lamp efficiency improves by 5–10% according to type. Secondly, it has been discovered recently that the light fluctuation at 100 Hz which occurs with conventional mains operation of fluorescent lamps, although not visible, is detectable in the human visual system. It is suggested that some individuals suffer a higher incidence of reported headaches and eyestrain as a result of this invisible fluctuation. Higher frequency lighting has been shown to minimise this problem and, as a result, improve productivity.

Variable light output electronic ballasts Now that electronic ballasts are widely used it has become possible to build in extra circuitry at modest cost in order to permit the light output of the lamp to be controlled. These controllable ballasts will respond to simple control signals and vary the light output of the lamp.

A good design should be able to vary the light output from 1% to 100% of full output. This is normally achieved by an extra-low-voltage control circuit connected to a simple variable resistor. Several ballasts would normally be connected to one resistor to control the lighting in a room. Such a set up is less expensive than conventional dimming circuits.

In some designs an interface can be provided which will link the ballasts to the output of a conventional dimmer without adding load. In this way a conventional tungsten load can be controlled along with the fluorescent lighting. The dimming range is normally restricted to 10–100% because of the dimmer circuit.

Not all ballasts can provide full control. Some will only operate reliably with special lamps. Some ballasts can only control the light output from 25% to 100%. Although this may seem a large variation (4:1), because of the way in which we see, it is only perceived to be about a 2:1 change in brightness at full light output. This degree of control is of little use except for minor energy management where the lighting levels can be raised and lowered to top up daylight over a limited range.

Controllable electronic ballasts can be linked together and controlled in a number of different ways. The ballasts can be linked to a full lighting management system connected to local controls, programmable clocks, occupancy sensors and daylight photocells.

Fluorescent tube replacement It is not easy to determine the end of the useful life of a fluorescent tube. Although failure to start will eventually occur due to exhaustion of the oxide coating on the electrode filaments, it is normally possible to justify replacement of the tube before this stage. As most installations of fluorescent luminaires are designed to give a planned illuminance, random replacement of tubes at end of life will result in a non-uniform illuminance, which is uneconomic when related to energy costs and labour costs for replacement.

Figure 21.19 indicates typically the inherent deterioration of the illuminance from the luminaires of a fluorescent tube installation, and the gains that result from regular cleaning and lamp replacement. It is assumed that the use of the installation is 3000 h/year.

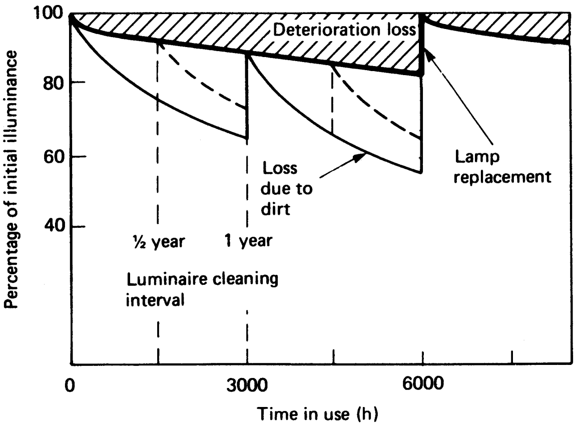


Figure 21.19 Effects of deterioration, cleaning and lamp replacement on the illuminance of a fluorescent-tube installation

Tube colours *Table 21.1* shows how the tube colours are graded in terms of lumen output efficacy and colour rendering quality. In choosing a tube colour a choice must be made between light output and colour, since tubes with high lumen output have only modest amounts of blue and red energy, whereas good colour rendering lamps have reduced yellow/green content and the tube lumen output is subsequently reduced.

A development in fluorescent tube phosphors is the multi-phosphor. Based on the principle that a mixture of red, green and blue light produces a white light, efficient red, green and blue phosphors are mixed in appropriate proportions to produce a white light when irradiated by ultraviolet light in a fluorescent tube. This produces a high-efficiency tube with good colour rendering for general applications. As the phosphors are costly, the tubes using them are more expensive and are frequently made in a diameter of 25 mm instead of 38 mm.

The characteristics of different fluorescent tubes are described and shown in *Table 21.1.*

Standard halophosphate lamps At one time these lamps were the best choice for general lighting because they combined acceptable colour with high efficiency. They have now been replaced by the superior multiphosphor lamps which give higher output, better colour and superior economy through life.

Special lamps These lamps have specific colour rendering characteristics.

Multiphosphor/triphosphor lamps These lamps are superior in colour quality and efficiency to standard halophosphate lamps. They therefore reduce installation costs because fewer luminaires are needed and also improve lighting quality. They are the primary choice for general lighting.

Deluxe multiphosphor lamps These lamps are superior in colour quality to normal multiphosphor/triphosphor lamps and are designed to replace the special lamps referred to previously, but with significantly better efficiency.

21.5.3.2 Compact fluorescent lamps

In recent years compact fluorescent lamps have been developed. For a given light output, compact fluorescent

Table 21.1 Fluorescent tube colours

Tube colour	*Light output relative to white (%)*	*Luminous efficacy** (lm . W^{-1})	*Colour rendering*	*Colour appearance*	*Application and remarks*
Standard halophosphate lamps					
White	100	45–65	Fair	Intermediate	A general-purpose tube which combines good lumen output with a white appearance. Warmer than daylight, but cooler than incandescence
Warm white	98	45–65	Fair	Warm	For general lighting where a warmer appearance than white is required. Incandescence effect, but without good red
Daylight cool white	94	45–65	Fair	Cool	For general lighting where a cooler appearance than white is required. Daylight effect, but lacking in red
Special lamps					
Northlight, colour matching	59	2–40	Excellent	Cool	For displays in lighting where a cool north skylight (winter light) effect is required, with normal red rendering. For colour matching
Artificial daylight	41	20–40	Excellent	Cool	Special tube with added ultraviolet to give a very close match to natural daylight. For colour matching cubicles
Natural	70	30–50	Good	Intermediate	For office and shop lighting to give a cool effect. Close to natural daylight but with a flattering red content
De luxe natural	49	15–25	Very good	Intermediate	For food and supermarket displays with meat or highly coloured merchandise. Combination of good blue and red rendering

*Based on total circuit power.

lamps have small dimensions compared with linear fluorescent lamps. This reduction in size is normally achieved by folding the discharge path.

These lamps have two major application advantages. Firstly, because they are available in similar sizes and light outputs to conventional filament lamps they can be used as replacements, either in existing luminaires or in new designs. They will use about 25% of the power of the tungsten lamp equivalent of similar light output and will typically last 10 times longer. Secondly, compact fluorescent lamps can be made smaller than their linear fluorescent counterparts. This means that smaller more attractive luminaires can be designed with similar light output to conventional fluorescent lamps, but without the need to be long and awkward in shape.

Therefore compact fluorescent lamps are widely used either for applications where, previously, tungsten lamps would have been used, such as decorative lighting in hotels, or for applications where fluorescent lamps would have been used but a more acceptable luminaire style or shape can be designed (e.g. a 500 mm luminaire can replace a 1200 mm × 300 mm luminaire).

Theoretically, there are many good reasons why tungsten lighting in the home should be replaced by compact fluorescent lighting. Despite the superior life and economy (the major cost of a lamp is the electricity it consumes), these lamps have not been widely used in the home. However, they are extensively used in industrial and commercial situations.

Compact fluorescent lamps can be divided into two broad categories: replacements for GLS lamps and light sources for new luminaires.

Replacements for GLS lamps Some lamps have integral control gear. They can be used as direct plug-in energy saving replacements for conventional lamps. The only factor to note is that some types are much heavier and rather more bulky than the lamps that they replace. Some lamps have integral electronic control gear. The main disadvantage of this type of approach is that when the lamp is thrown away then the expensive integral control gear is thrown away with it. An alternative approach is to provide adapters which can be plugged in to lamp sockets and convert them to compact fluorescent use.

Light sources for new luminaires Some lamps were developed to make possible the design of compact luminaires with all the advantages of fluorescent lamps. The use of these lamps permits plastic and other materials to be used close to the lamps. This increases the scope for attractive designs using novel materials. There is a wide range of lamps with light output suitable as substitutes for conventional lamps of 100 W and below. However, in commercial and industrial lighting, greater light outputs are required.

21.5.3.3 Cold cathode lamps

By comparison with conventional hot-cathode fluorescent lamps, cold-cathode lamps, which are often used in advertising signs, rely upon a relatively high lamp voltage for establishment of the arc. Electrical isolation of such lamps is typically achieved by means of a 'fireman's switch' usually located on the frontage of premises.

The electrodes used for cold-cathode lamps are typically plain nickel or iron cylinders whose size is substantial in order to limit the current density at their surface to an acceptably low value.

Lamp life values for such lamps are much higher than for hot-cathode fluorescent lamps.

21.5.3.4 Induction lamps

The induction lamp is also referred to as the 'electrodeless lamp'. It relies upon both magnetic and fluorescent principles for its operation. The constructional features of the lamp are shown in *Figure 21.20*.

Energy transfer using magnetism (following the electrical transformer principle) is employed with the low pressure mercury filling in the lamp acting as a secondary coil of the transformer. A high frequency alternating electrical current in the primary winding is supplied from an external source. The current induced in the mercury vapour gives rise to emission of ultraviolet radiation in a similar manner to that in a conventional fluorescent lamp and the phosphor coating on the inside of the lamp envelope converts this UV radiation into visible light. The lamp life is typically 60 000 h, which makes the use of such lamps in relatively inaccessible areas particularly beneficial.

21.5.3.5 High-pressure mercury lamps

Construction The lamp consists of a quartz glass (pure fused silica) arc tube, enclosed within a borosilicate outer envelope. The envelope can be tubular, but is normally ellipsoidal to ensure an even outer-envelope temperature. (Ellipsoidal outer envelopes operate at about 550 K, compared with 800 K for the hottest parts of tubular envelopes.)

The arc tube contains a controlled quantity of mercury sufficient to produce the desired pressure at operating temperature.

Electrodes, in the form of helices of tungsten wire, about a tungsten or molybdenum shank, are fitted at opposite ends of the arc tube. Emissive material is coated onto the electrodes (or may be held inside in pellet form). To assist in starting the lamp, an auxiliary electrode is mounted in close proximity to one of the main electrodes and is connected to the other electrode via a high resistance (10–30 kΩ). The electrodes are sealed into the quartz glass arc tube by means of molybdenum foil (as with tungsten halogen lamps).

The outer envelope (*Figure 21.21*) is filled to a pressure of 0.25–0.65 atm with either nitrogen or a nitrogen–argon mixture.

High-pressure mercury fluorescent lamp The quartz glass arc tube transmits ultraviolet light and enables a phosphor coating to be used on the inside of the outer envelope. The phosphor improves the colour rendering properties and luminous efficacy. Phosphors have upper limits of operating temperature and the use of ellipsoidal bulbs ensures the minimum size of envelopes. Improvements in phosphors to give operation at higher temperatures have resulted in smaller envelope sizes.

High pressure mercury vapour lamps (see *Figure 21.22*) have efficacies of about 58 lm . W^{-1} with acceptable colour rendering for factories, storage areas, offices, etc.

High-pressure mercury fluorescent reflector lamp This lamp (*Figure 21.23*) is identical with the high pressure mercury vapour lamp, except that the outer envelope is shaped to form a reflector. Titanium dioxide is deposited inside the conical surface of the outer envelope: this reflects about 95%

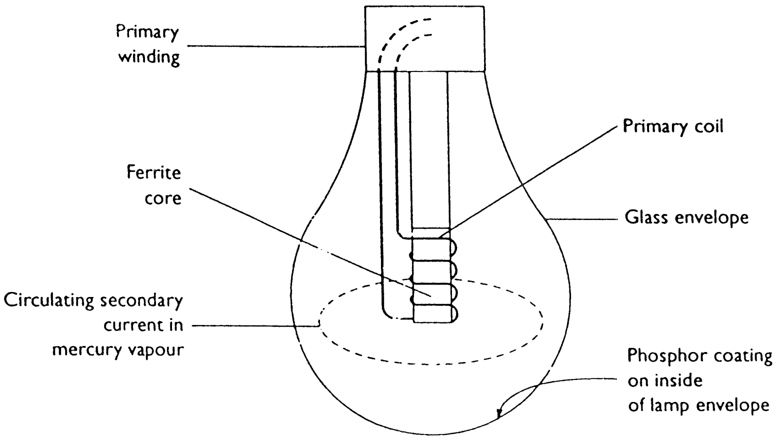


Figure 21.20 Induction lamp

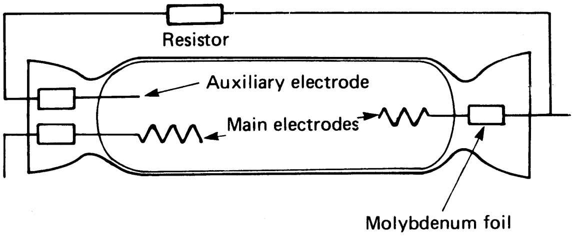


Figure 21.21 Arc tube construction of a high pressure mercury lamp

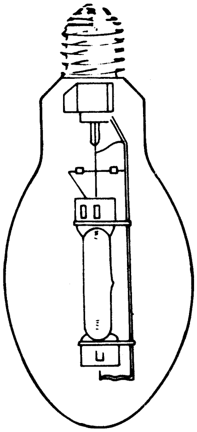


Figure 21.22 A high pressure mercury lamp with phosphor coating

of all the light in a diffuse manner. The phosphor is applied over this coating. The front face is left uncoated (although it may be etched or have a diffusing coating of silicon dioxide) and about 90% of the light is emitted through this opening. The lamp is less efficient but has a directional light output, suitable for installations where the luminaires have to be mounted high up (as in storage areas, hangars, etc.), and where dirty conditions obtain.

High-pressure mercury-blended lamp By including a filament within the outer envelope the need for special control gear can be eliminated, as the filament can act as a ballast. The efficacy of the lamp (12–25 lm . W^{-1}) is poor compared to a high pressure mercury vapour lamp and inductor, but the lamp has two important advantages: (1) it can be fitted into any standard lampholder as a direct replacement for a tungsten lamp of the same rating, and will produce more ultraviolet and visible light; and (2) unlike other mercury lamps, it will emit some light from the filament immediately upon switching on.

High-pressure mercury-metal halide lamps The efficacy of high pressure mercury lamps is lowered because regions of the lamp are at potentials too low for the excitation of mercury. By adding suitable metals with lower excitation potentials to the arc tube, it is possible to increase the light output and improve colour rendering. The only suitable metals are highly reactive. These would damage the quartz glass arc tube and seals. By adding the metals (sodium, thallium, gallium, scandium and others) in the form of halides (usually iodides), these problems can be eliminated.

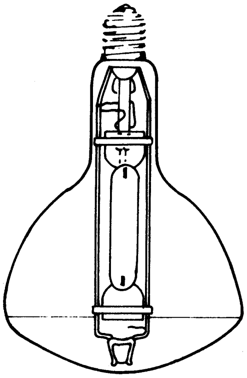


Figure 21.23 A high pressure mercury lamp with phosphor coating and integral reflector

The halides dissociate in the arc itself, but recombine at the arc tube wall.

The metal halide lamps are better than their counterparts, in both colour rendering and efficacy (85 lm . W^{-1}). *Figure 21.24* shows a high pressure mercury-metal halide lamp.

21.5.4 Sodium Lamps

21.5.4.1 Low-pressure sodium lamps

The low-pressure sodium lamp is characterised by its monochromatic yellow light, which consists of two radiation lines (resonant doublet) at 589.0 and 589.6 nm. The lines are close to the maximum spectral sensitivity of the eye (555 nm) and the lamp is therefore efficient. Efficacies of over 150 lm . W^{-1} are typical.

The lamp has poor colour rendering properties. Because the light is monochromatic, it is restricted to applications where the colour of the source and colour discrimination can be sacrificed for high efficacy. For example, the lamp is used for floodlighting and street lighting.

Construction and operation The lamp consists of a long arc tube of glass construction, known as 'ply tubing', filled with low-pressure gas (usually neon + 1% argon). The lamp also contains a small quantity of metallic sodium (solid at room temperature), which provides a pressure of about 0.66 Pa in the lamp when operating. Precautions must be taken to prevent the sodium from attacking the lamp seals. At each end of the arc tube is a tungsten electrode of coiled-coil,

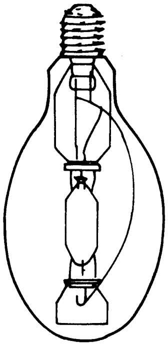


Figure 21.24 A high pressure metal halide lamp

triple-coil or braided construction (similar to those in tubular fluorescent lamps) with an emissive coating (barium oxide or similar material).

The temperature of the arc tube must be maintained at about 270°C in order to successfully vaporise the correct amount of sodium to give a vapour pressure of about 0.66 Pa. It is therefore essential to avoid excessive heat loss if this temperature is to be maintained. In early lamp designs a Dewar flask was placed around the arc tube.

Modern lamps have an outer glass envelope enclosing the arc tube, and the space between the two is fully evacuated. In addition, the outer envelope is coated with an infrared reflecting film (bismuth oxide, tin oxide or gold) which transmits light but reflects heat back onto the lamp.

The requirements for efficient operation of a sodium lamp are: (1) the arc voltage gradient must be low (long arc tubes for a given power), and (2) the current density must be low (arc tubes must have a large diameter). Sodium vapour readily absorbs light at the resonant doublet wavelengths, and therefore light generated in the centre of the arc is reabsorbed by the vapour; thus, only the outer surface of the arc emits light. This conflicts with the need for a large-diameter arc tube, and demands a compromise.

Sodium, especially hot sodium vapour, is highly reactive and attacks any glass with more than a small proportion of silica in it (i.e. almost all normal glasses and quartz glass). Special glasses have been developed with low silica content which resist the attack of sodium vapour, but they are expensive, are difficult to work and are attacked by moisture. Hence, ordinary soda-lime glass tubing has a coating of this resistant glass flashed onto its inside surface, and the resultant cheap, easily worked material is known as ply tubing.

Unless checked, sodium vapour readily migrates along the lamp to the cooler parts. To prevent this, small protrusions are moulded into the arc tube. They project out from the arc tube and are therefore slightly cooler than the surrounding wall. They act as reservoirs for the sodium metal and help to maintain the correct vapour pressure at all points along the lamp.

A long arc tube is folded into a tight U shape (*Figure 21.25*). Mutual heating is provided by the two arms of the arc tube, but also each arm absorbs any light from the other arm which may strike it. The two effects are almost self-cancelling, but do produce a slight improvement in efficacy. The resultant lamp is fairly compact, with the advantage that all of the lamp connections are at one end. A single-bayonet lamp cap can therefore be used. The lamp efficacy is around 100 lm . W^{-1}.

When a sodium lamp is first switched on, the sodium is all present as solid metal. An arc discharge cannot therefore occur unless the sodium is first vaporised. For this reason a mixture of neon and argon is used in the lamp. The initial discharge occurs through this gas; the sodium metal is vaporised by the heat from this discharge, and slowly takes over.

The mixture of neon and argon (1%), known as a ‘Penning mixture’, reduces the starting voltage required. The energy required to *excite* neon is slightly higher than that to *ionise* argon. Electrons passing through the gas collide with the main gas (neon) and excite the atoms, which may collide with argon atoms giving up their energy by ionising the argon and producing an extra electron. This mixture reduces the starting voltage by typically 30–50%.

All low pressure sodium lamps when first switched on produce a distinctive red neon glow. Should sodium migrate from any part of the lamp, that part will also exhibit the red neon glow.

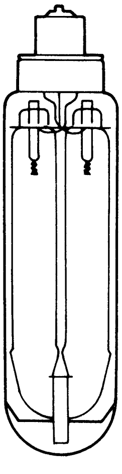


Figure 21.25 A low pressure sodium lamp

The effect of the Penning mixture is to make the starting voltage almost independent of ambient temperature. A low pressure sodium lamp can therefore be restruck when hot within about 1 min.

Although electrodes are fitted at each end of the arc tube, it is not normal to provide them with a heating current; and the two ends of an electrode are connected together.

21.5.4.2 High pressure sodium lamps

If the sodium vapour pressure in a low pressure discharge tube is raised by a factor of 10^5, the characteristic radiation is absorbed and broadened, greatly improving the colour rendering. However, hot sodium vapour is highly reactive, destroying or discolouring conventional arc tube materials; further, to achieve a high vapour pressure the coolest region of the arc tube must have a temperature of 750°C. These phenomena, known in the 1950s, were not exploited until the development of a translucent ceramic material—isostatically pressed doped alumina—capable of operating at temperatures up to 1500°C and of withstanding hot sodium vapour. The difficult process of sealing electrodes into the ends of the arc tube has also been solved. Typical methods are (a) brazing a niobium cap to the alumina tube, and (b) using hermetically sealed sintered ceramic plugs holding the electrodes.

Most high pressure sodium lamps have an arc tube containing metallic sodium doped with mercury and argon or xenon. Radiation of light is predominantly from the sodium. The mercury vapour adjusts the electrical characteristics, and acts to reduce thermal conductivity and power loss from the arc. Argon or xenon aids starting. The arc tube is sealed into an evacuated outer jacket to minimise power loss and to inhibit oxidation of the end caps, lead wires and sealing medium. Typical are tube operating temperatures are 700–1500°C, and efficacies of 100–200 lm . W^{-1} are achieved.

Starting is effected by high-voltage pulses (2–4.5 kV) to ionise the xenon or argon gas. The ionisation heats the lamp and the sodium vapour discharge takes over. The mercury vapour does not ionise, as its ionisation potential is higher than that of sodium, but its effect is to increase the lamp impedance, raising the arc voltage from about 55 V to 150–200 V. Electrodes are not heated during lamp operation. A hot lamp, after extinction, will not restart until cooled, unless 'hot-restart' ignitors (giving, e.g. 9 kV pulses) are provided.

The conventional high pressure sodium lamp (*Figure 21.26*(*a*)) has an outer envelope, which is elliptical and coated with a diffusing material. Tubular and double-ended versions are available as shown in *Figure 21.26*(*b*) and *Figure 21.26*(*c*).

It is interesting to note that, although the low pressure sodium lamp is more efficient than the high-pressure version, the large dimensions of the former make accurate optical control difficult. Furthermore, the luminaires are large, cumbersome and expensive. High pressure sodium lamp luminaires are therefore the better choice for many applications, and only in street lighting does low pressure sodium find a major application. High pressure sodium lamps are employed for street lighting, floodlighting and industrial and commercial interiors.

By increasing the xenon pressure in a high pressure sodium lamp and making some other changes, the output of the lamp can be improved without any loss of life or colour. The lamp efficacy improves by about 10–20% and the light output depreciation of the lamp is improved. The only penalty is that the lamp needs a much higher starting voltage (i.e. a different ignitor is needed).

If the internal pressure of a high pressure sodium lamp is increased then the colour quality and colour temperature of the light is improved at the expense of life and efficiency (life reduced by about 50% and efficacy by about 25%). These lamps are known as 'deluxe high pressure sodium lamps'. The colour rendering index is normally improved from 21 (class 4) to about 65–70 (class 2). This makes the lamp acceptable for merchandising applications and other areas where good colour is an important consideration. The lamps are widely used for lighting offices (via up-lighters) and for commercial lighting. The lamp is warm in appearance and for some applications this may be unacceptable. A recent development is the low wattage 'White' high pressure sodium lamp with very high colour rendering which has been designed for display lighting purposes. These lamps need special electronic control gear.

21.5.5 Control gear

The term is used affectionately to describe the equipment that is necessary for the safe and efficient operation of discharge lamps. The function of the control gear is essentially twofold: it assists in providing a high voltage pulse to enable the arc to be established within the discharge tube in the lamp and once the arc has been established the control gear takes on the role of a current limiting device in order to limit the current flowing through the lamp. Discharge lamps exhibit a negative resistance characteristic.

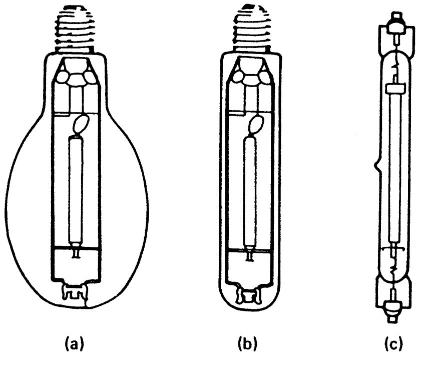


Figure 21.26 High pressure sodium lamps: (a) SON lamp; (b) SON/T tubular lamp; (c) SON/TD double-ended linear lamp

It has to be appreciated that heat is produced during normal operation of lamps and control gear. Nevertheless many items of control gear have recommended maximum temperatures and it is essential that such values be not exceeded.

Individual items of electrical and/or electronic equipment used include ballasts, transformers, ignitors and power factor correction capacitors. Some items of control gear will consume power from the supply and the resulting electrical energy costs will have to be borne by the consumer. It is therefore beneficial to be aware of the power ratings of control gear when considering the economics of lighting.

21.5.6 Electroluminescent devices

Electroluminescence is the emission of light from a semiconductor under the action of an electric field. The process involves heat only as a by-product of the mechanism, which is essentially a 'cold' one. The phenomenon is of commercial interest because of its relatively highly efficient production of visible light.

Characteristics Luminescence decays with time exponentially, so that is convenient to quote the half-life of an electroluminescent source. The half-life varies from hundreds to millions of hours, depending on the type and purity of the semiconductor materials used. The sources emit light in comparatively narrow spectral bands, producing colour without the use of filters. Sources can be of almost any size, down to areas of less than 0.05 mm^2. The surface brightness is, however, comparatively low.

In an electroluminescent material two processes must take place. First, an adequate supply of electrons must be available in the conduction band, made possible by using an electric field to raise the energy level of electrons in the valence band. Second, the electrons must give up their energy in the form of photons and so return to the valence band. The recombination process is dependent on the 'forbidden gap', the wavelength λςof the emitted radiation being defined by the energy jump E through the relation λς$=hc/E$, where h is Planck's constant and c is the free-space velocity of electromagnetic waves. Consequently, materials with a bandgap E of 1.65–3.2 eV are capable of producing visible light by electroluminescence, provided that the electron return from the conduction to the valence band is not made in two or more stages by reason of the presence of lattice impurities; but if this is the case, luminescence can be obtained with materials having an intermediate gap energy.

Materials The requirements for an electroluminescent material emitting in the visible spectrum are, generally, that it should have a bandgap of at least 2 eV, be susceptible to both p- and n-type 'doping', and should have either a direct bandgap or an activator system permitting 'steps'. Typical semiconductor materials are ZnS, GaP, GaAs and SiC.

The preparation of luminescent panels based on ZnS involves baking pure zinc sulphide with various dopants such as manganese, copper and chlorine. The sintered mass is ground to a particle size of the order of 10 μm, washed and dried, and mixed with a suitable resin. The suspension is coated on to a glass substrate supporting a very thin layer of gold or SnO, to form one electrode. The other electrode, an evaporated layer of aluminium on the rear surface of the

Table 21.2 Lamp characteristics

Lamp type	*ILCOS lamp coding*	*Typical lamp life* (hours)
Tungsten filament	I	1000–2000
Tungsten halogen	HS	2000–4000
Low pressure	FD (tubular)	6000–15 000
Mercury (fluorescent)	FS (compact)	8000–10 000
High pressure mercury	QE	14 000–25 000
Metal halide	M	6000–13 000
Low pressure sodium	LS	11 000–22 000
High pressure sodium	S	12 000–26 000
Induction	XF	60 000

cell, also acts as a reflector. The small cells are produced from GaP crystals, with areas selected for fabricating electroluminescent diodes. They are cut into 0.5 mm squares, and a p–n junction is formed by alloying a tin sphere into the GaP, which is doped with zinc to produce the junction. The diode structure is completed by alloying a Au–Zn wire into the GaP to make an ohmic contact, and then connecting a wire to the tin sphere.

21.5.7 Lamp life

Table 21.2 gives details of lamp life values.

21.6 Lighting design

21.6.1 Objectives and Criteria

To design a lighting scheme the basic objectives must be first established. What sort of tasks will be carried out in the area to be lit? What mood needs to be created? What type of lighting will create a comfortable, pleasant environment? The objectives having been established, they have to be expressed as a series of lighting criteria. For example, what level of illuminance is required? How much glare is acceptable?

The designer then plans a scheme that will best meet the criteria by selecting the appropriate luminaires and considering the practical problems.

21.6.1.1 CIBSE code for Interior Lighting

The Chartered Institution of Building Services Engineers publishes a code of recommendations for the lighting of buildings. It puts forward ideas and methods representing good modern practice and is concerned with both quantity and quality of light.

The CIBSE code for Interior Lighting deals with: how building design affects lighting; lighting criteria; lighting and energy consumption; design methods; lighting equipment; and methods of maintenance. In addition, there is a schedule giving specific recommendations for a wide variety of areas such as assembly areas, factories, foundries, schools, hospitals, shops and offices.

For each entry a maintained illuminance and position of measurement is quoted. The amount of discomfort glare that can be tolerated is given by a limiting glare index. A list of suitable lamp types and their colour appearance is given together with notes on special problems that may be encountered.

The recommended maintained illuminance—in other words, the recommended illuminance that should be provided for a particular application—is a useful guide for the designer. But it is only a recommendation: in some circumstances it should be increased. For example, if errors could have serious consequences in terms of cost or danger, or if unusually low reflectances or contrast are present in the particular task, or if tasks are carried out in windowless interiors where the recommended standard service illuminance is less than 50 lx, the illuminance level should be increased. On the other hand, there are circumstances (e.g. when the duration of the task is unusually short) when the designer would use his judgement to reduce the standard service illuminance. *Table 21.3* gives typical recommended maintained illuminance values.

21.6.1.2 Uniformity

In addition to providing the correct illuminance, the uniformity of the lighting level is also important. The uniformity is expressed as the ratio between the minimum and the average illuminance over the working area. It should not be less than 0.8 in areas where the tasks are performed.

21.6.1.3 Reflectance

Reflectances should also be considered. The effective reflectances of walls in a room should be between 0.3 and 0.7; the ceiling should have a reflectance of 0.6 or greater; and the floor should have a reflectance of between 0.2 and 0.3 (see *Figure 21.27*).

21.6.1.4 Illuminance ratio

The ratio between the illuminance on the wall and that on the task, and between the ceiling and that on the task, is also important. The wall illuminance should be between 0.5 and 0.8, and the ceiling illuminance should be between 0.3 and 0.9, of the task illuminance (see *Figure 21.27*).

For normal working environments, if the reflectances and the ratios between wall illuminance and the task, and between ceiling illuminance and the task, are outside the recommended levels, they will be unacceptable. However, there are exceptions if a particular mood or atmosphere is being created.

21.6.1.5 Modelling and shadow

The direction of light and the size of the luminaires in an interior affect highlights and shadows, influencing the appreciation of shape and texture. The term ‘modelling’ is used to describe how light reveals solid forms. It may be harsh (the contrast may be excessive and produce deep shadows) or flat (the light provides low contrast with little shadowing). Either extreme occurring in the lighting of a general working area makes vision difficult or unpleasant. Therefore, the aim of good lighting design must be to produce a suitable compromise between the two, although it may not be the same for different applications. Texture and surface details are best revealed by light with fairly strong directional characteristics. Reflections of lamps on polished surfaces may veil what one needs to see, reducing contrast and handicapping one’s vision.

Table 21.3 Typical recommended maintained illuminance values

Workplace	*Typical recommended maintained illuminance values* (lux)	
Engineering workshops	rough e.g. bench work	300–400
	detailed work	700–800
	inspection	500–2000
Clothing and textile	preparation	300–400
	cutting	750–850
	inspection	1500
Construction sites	site roadways	5–15
	general areas	20–25
	crane loading	100–150
Electronics equipment manufacture	component assembly	300–1500
	printed circuit board work	500–750
	inspection	1000–1500
Food and drink	abattoirs	500–750
	bakeries	300–500
	breweries	300–750
	dairies	300–500
	flour mills	300–500
Metal working	iron and steel mills	300–500
	foundries	300–500
	inspection	500–1500
Furniture and timber	sawmills	300–750
	workshops	300–750
	furniture manufacture	300–750
	upholstery	500–1500
Glass production	general production	300–750
	inspection	1000
Health care premises	general wards	150–250 (day) 3–5 (night)
	maternity wards	200–1000
	laboratories	300–750
	operating theatres	500–50 000
Paper and printing	paper mills	300–750
	printing works	300–750
	inspection	1000

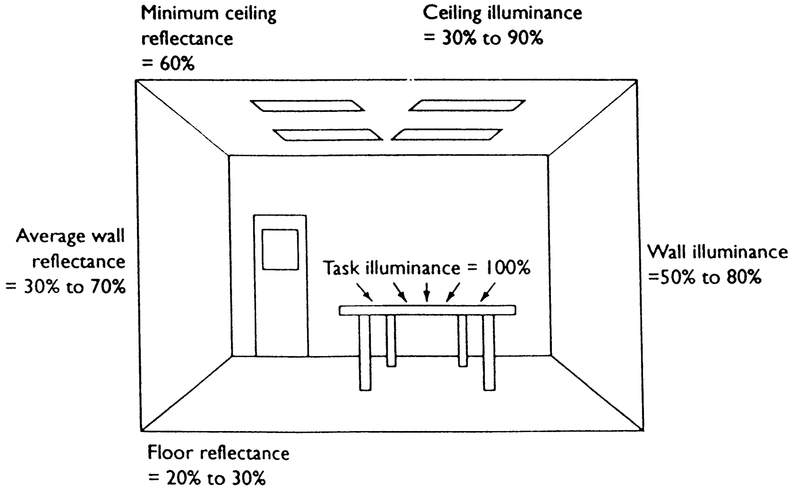


Figure 21.27 Typical room surface illuminance ratios. Illuminance values quoted are relative to a task illuminance of 100 per cent

21.6.1.6 Glare

The visibility of a working task is influenced to a large extent by any sources of glare within the visual field. One definition of glare is that it is any excessive variation in luminance within the visual field. Glare can be conveniently divided into two main groups i.e. disability glare and discomfort glare.

Glare can be thought of as 'direct' when it occurs as a consequence of bright sources directly in the line of vision, or alternatively as 'reflected' when light is reflected onto surfaces that have high reflectance values. Factors involved in the production of direct glare include the luminance of the light source and the location of the light source.

A form of glare that will disable an individual from carrying out a particular visual task is referred to as disability glare. An everyday example of disability glare occurs when an individual looks at the headlights of a stationary vehicle during darkness. Under these circumstances it is impossible to discern the scene at the sides of the vehicle immediately behind the headlights. The glare disables the individual from carrying out the visual task. The magnitude of the disabling effect experienced with disability glare is unlikely to occur with discomfort glare. An individual will experience a feeling of discomfort when the exposure time is prolonged. Disability glare and discomfort glare are the major forms of glare. Discomfort glare is more prevalent in interiors and often occurs as a consequence of either a badly designed lighting installation or a change of use of the interior from that which it was originally intended. In addition it is possible to assign numerical values to the degree of discomfort glare prevailing in a given interior. It is therefore possible, at the design stage, to eliminate any such adverse effects.

A method used for calculating the 'limiting glare index' (LGI) is shown in detail in the CIBSE Code for Interior Lighting. The method is a 'step-by-step' process where an initial and uncorrected glare index value is obtained from published tables. In these tables the major dimensions of the room interior (length and width) are given in multiples of the mounting height H which is taken as the distance between the horizontal lines passing through the eye level of a seated observer and the centre line through the luminaire(s). The eye level of a seated observer is taken, initially, as 1.2 m above floor level.

A second stage to the calculation involves applying two correction factors to the initial glare index value obtained. These factors involve variations in (a) the luminous flux of the luminaire and (b) any variation in mounting height from the normal seated eye level of 1.2 m.

Once the 'final glare index' value is calculated it is compared with reference values of limiting glare index (LGI), which are published in references e.g. CIBSE Code for Interior Lighting. Should the final glare index value calculated be lower than the LGI value the development of discomfort glare is unlikely.

It is also possible to categorise glare as either 'direct' or 'reflected'. Direct glare occurs when the origin is bright sources. Reflected glare occurs when light is reflected from specular or mirror-like surfaces. When considering glare it is essential to consider the luminance of the source, the position of the source, the luminance distribution and the time duration of exposure. The maximum value of luminance, which is tolerable by the eye as a result of direct viewing, is approximately 7500 cd . m^{-2}.

The visual comfort of an individual is influenced by the distribution of luminance across the immediate field of vision and furthermore by the luminance of the environment when seen by individuals who glance away from their work.

Ideally the work surrounds should be less bright than the work itself. Optimum visual comfort occurs when the work is slightly brighter than the near surround. This in turn should be slightly brighter than the far surround.

The ideal ratio for distribution of luminance across a task is usually taken as 10 : 3 : 1. It is possible to obtain a 'trade-off' in luminance values, away from a visual target by using different materials. *Figure 21.28* shows the ideal luminance distribution across a visual task.

The luminance contrast of a visual task will be influenced by, inter alia, the reflectance values of the task and furthermore upon the manner in which the task is lit. Task materials with matt finishes will reflect the incident light equally in all directions and it follows that the direction of the incident light falling on the task material is unimportant. Conversely if the task material has a specular finish then the direction of the incident light is important.

When the image of a source of high luminance, e.g. a luminaire or the sun, is reflected from a surface being viewed by an individual then veiling reflections will be created. An example of this is experienced when looking at a display screen. If the geometry of the individual, screen and luminaire is not controlled, an out-of-focus image of the luminaire will be seen in the screen. This will throw a veil of light on the front of the screen, hence the term veiling reflections, and some of the text on the screen will become illegible, see *Figure 21.29*.

Downlighters with a strong downward component of light distribution will produce a significant loss of task visibility due to veiling reflections. A lighting installation should ideally provide a minimum directional component immediately above the task itself. Light should preferably reach the task from wider angles, which will reduce glossy reflections seen by the individual in the visual task.

21.6.1.7 Colour rendering of lamps

Generally the apparent colour of objects seen under an artificial lighting installation is of some importance, sometimes it is vital, as for instance in the buying and selling of foodstuffs, the preparation of paints and dyes and the matching of silks, cottons, etc., to fabrics and to one another.

A red article looks red because it reflects red light more strongly than other colours of light, but it can only do so if there is some red light present for it to reflect. Similarly, a green article can only look green if there is some green light present, and so on. It follows that if all colours are to be seen well, the light must contain a mixture of all possible colours of light of roughly equal strength. Such a light will look white, or nearly so. Unfortunately, it is possible for a

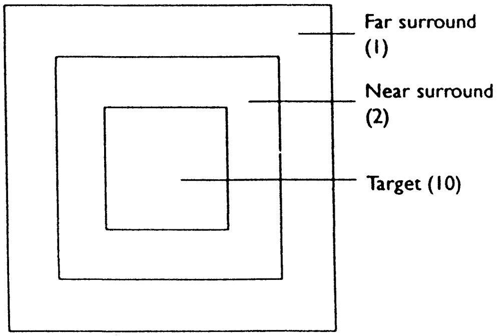


Figure 21.28 Ideal luminance distribution across a visual task

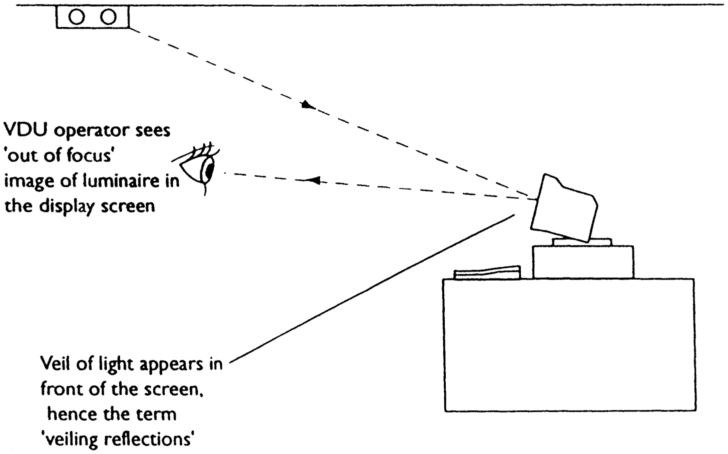


Figure 21.29 Veiling reflections

light to look white even though lacking some of the possible colours (e.g. the light of an ordinary mercury lamp can in certain circumstances look fairly white, though it lacks more colours than it contains, and the poor colour rendering of this type of lamp is well known).

Filament lamps of all types emit all possible colours of light, but in far greater strength at the red end of the spectrum than at the blue end. Thus, red and yellow objects appear in stronger colour than in natural daylight, whereas blues are weak and somewhat muddy in appearance. This, however, is a distortion familiar to most people, who have learned to make allowance for it in choosing decoration materials, etc. The light of a 'deluxe warm white' fluorescent lamp is very similar to that to a filament lamp.

For accurate colour judgement a light similar to north-sky daylight is necessary. An 'artificial daylight' fluorescent lamp has been developed which meets the requirements of BS 950:1967. The 'colour-matching' or 'north-light' type of fluorescent lamp gives a close approximation to north-sky light and is found entirely satisfactory in many industries critically concerned with colour, but this very white light is perhaps too 'cool' in appearance to be used alone in interiors of a more domestic nature, where a 'warm' light is traditional. The other colours of fluorescent lamps are mainly of higher efficiency than the previously-named two types, and the choice will lie between them according to the relative importance of their efficiency and their particular colour rendering properties.

21.6.1.8 Display screens

When a display screen equipment operator is viewing a screen, other parts of the interior will be within their visual field and this will lead to problems with adaptation. Light scattered in the eye will reduce the contrast of the image subsequently formed on the retina. The effect of this is to produce impaired vision. In addition if the display screen operator momentarily glances away from the screen, transient changes in adaptation will occur and again vision can be impaired.

There are several options available to the designer in an attempt to produce optimum lighting conditions. The most simple involves a repositioning of one or more of the light sources, the screen and the operator.

It will be evident that any re-positioning of the light source is the least practical since in many cases luminaires are ceiling-mounted in fixed locations. There are however much simpler remedies, for example the ergonomics of the operator is highly significant.

In interiors where the installation of uplighters is inappropriate then downlighters can be used. In such situations restrictions are placed upon the luminous output characteristics of the luminaires. In an attempt to avoid high-luminance reflections appearing on display screens it is important to use luminaires with an appropriate luminous intensity distribution, which subsequently limits the luminance seen by screen operators.

If the relationship between the terminal and operator could be established then it would be possible to determine the appropriate geometry, which in turn would allow calculation of luminaire characteristics necessary to prevent direct vision of the light sources. However such information is seldom available due to the wide range of tasks and screen types in use.

The work activities of those who use display screen equipment are covered by both EC and UK legislation, which specifies minimum standards for the visual environment, including the lighting conditions. In order to satisfy the legislation, display screen equipment tasks must be classified in accordance with the conditions specified therein. The tasks can influence the magnitude and severity of reflections likely to be encountered on the screen. The three categories relative to areas where display screen equipment is used are designated Category 1, Category 2 and Category 3. Luminaires for use in each of the three areas specified are known as Category 1, Category 2 and Category 3 luminaires. For each of these luminaire categories the luminance above a predetermined angle, referred to as the critical angle, is limited to 200 candelas per metre^2. The values of critical angles referred to, for categories 1, 2 and 3 luminaires, are 55°, 65° and 75° respectively. *Figure 21.30* shows the geometry of the critical angles described.

Category 1 luminaires are used typically where there is a high number of screens, in an area where extensive use is likely and where errors occurring as a consequence of misreading the data on the screen are unacceptable. Category 1 luminaires are typically used in air traffic control rooms and emergency services control rooms. Category 2 luminaires tend to be used far more than other Category

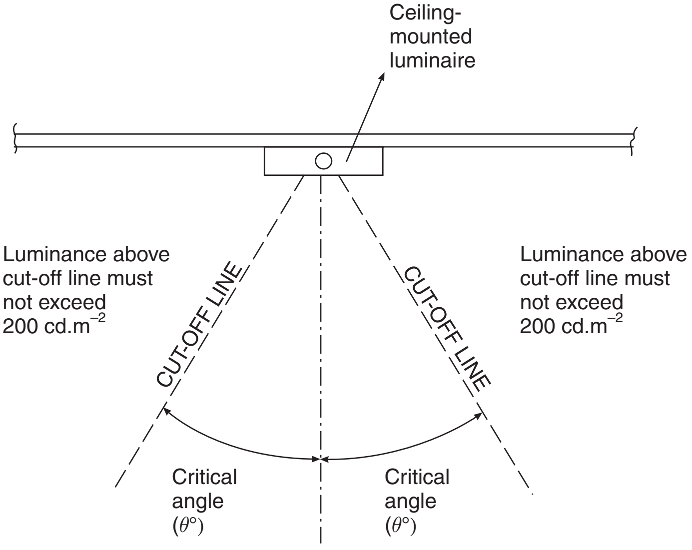


Figure 21.30 Critical angles for downlighter luminaires used in VDU areas

luminaires and their use is typically in areas where display screen equipment is located at each workstation. Category 3 luminaires are usually used where screen usage is random and where the number of screens is relatively low.

The Health & Safety (Display Screen Equipment) Regulations 1992, under the Health & Safety at Work Act 1974, refers to minimum health requirements in relation to work with display screen equipment. Employers must take steps to ensure that all workstations under their control comply with the regulations. In general terms the regulations require lighting conditions which are satisfactory and which ensure that an appropriate contrast between display screen equipment and the background environment be provided. Any glare or distracting screen reflections must be prevented.

21.6.2 Luminaires

The luminaire formerly referred to as the 'light fitting' provides support, protection and means of electrical connection to the lamp, which is contained within the luminaire. Additionally the luminaire has to be able to operate safely and to withstand the environmental conditions in which it is likely to be installed.

Luminaires may also be classified according to the following categories: type of protection provided against electric shock, the degree of protection provided against the ingress of dust or moisture, type protection provided against electrical explosions and according to the characteristics of the material of the surface to which the luminaire can be fixed.

Those luminaires that are designed for use internally, and those for use in some external applications, will normally operate efficiently in dry and well-ventilated atmospheres.

Some luminaires are installed in atmospheres that are far less acceptable. In order to be able to perform within the environments likely to be encountered, the equipment must therefore be manufactured so as to comply with strict specifications. Such environments are referred to as hostile or hazardous. Examples of hostile areas include: high humidity conditions (requiring drip-proof equipment), dusty and corrosive atmospheres, and food factories (where the interior walls, floors and ceilings are required to be hosed down).

Hazardous atmospheres are usually created by the presence of flammable or explosive dusts and gases in the atmosphere.

21.6.2.1 Optical control of light output from luminaires

When a bare lamp is used, i.e. one without any form of control of the directional qualities of the light emitted, then the distribution of light is likely to be completely unacceptable. Furthermore the bare lamp is also likely to create a source of disability glare to the occupants of the interior. It is likely that the lighting installation will be uneconomical and whilst some fraction of the light output from the bare lamp will reach the working plane either directly or indirectly, the efficiency of the installation will be relatively low.

It will be clear that some means of control of the light output from the bare lamp is essential and four of the most widely used methods are detailed:

Obstruction When a bare lamp is installed within an opaque enclosure, which has only one aperture from which the light can escape, then the light distribution from the basic luminaire will be severely limited (*Figure 21.31*).

Reflection This method of light control uses reflective surfaces, which may range from matt to specular. By comparison with the 'obstruction' method of light control, reflection is more efficient. With reflection, stray light is collected by the reflectors and then redirected (*Figure 21.32*).

Diffusion When a lamp enclosure, is constructed of a translucent material, two benefits will accrue. The apparent size of the light source is increased and simultaneously there is a reduction in perceived brightness. One disadvantage as a consequence of the use of diffusers is that they absorb some of the light emitted from the source itself and so therefore there will be a reduction in the overall

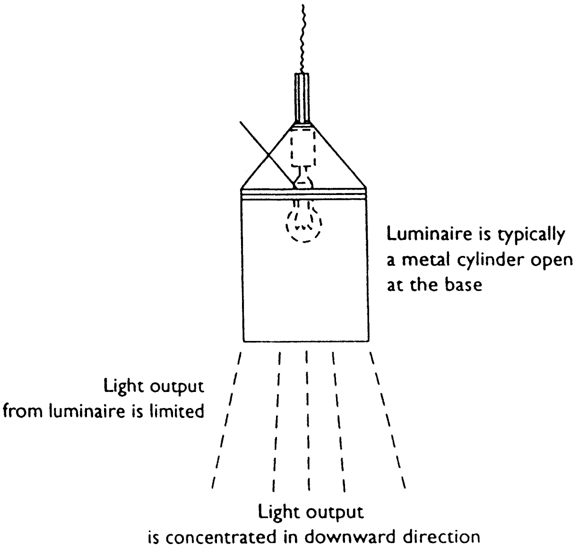


Figure 21.31 Light control by obstruction

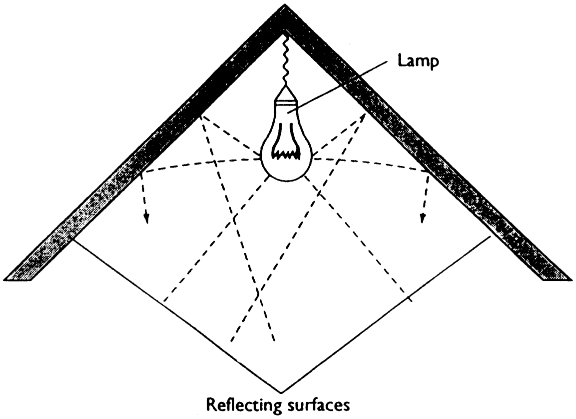


Figure 21.32 Light control by reflection

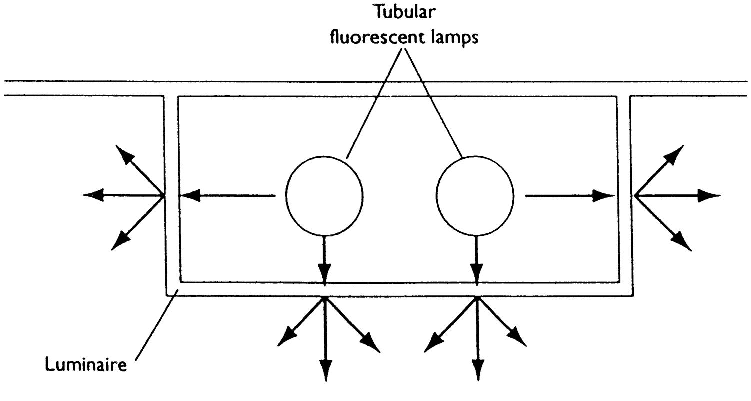


Figure 21.33 Light control by diffusion

luminaire efficiency. *Figure 21.33* shows the concept of diffusion.

Refraction This method utilizes the prism effect so as to bend the light output from the bare lamp in the required direction. This method of light control has the benefits of effective glare control and additionally of producing an acceptable level of luminaire efficiency (*Figure 21.34*).

21.6.2.2 Downlighter luminaires

Those luminaires classified as downlighters will emit the major proportion of their light output in the downward direction. They are typically ceiling-mounted or ceiling-suspended. When compared with uplighters, downlighters are far more efficient since they provide direct lighting of the working plane, and do not rely totally on light reflected from room surfaces.

21.6.2.3 Uplighter luminaires

Those luminaires that are classified as uplighters will emit the major proportion of their light output in the upward direction. *Figure 21.35* shows the general principle of lighting using uplighters. When compared to downlighters, uplighters are relatively inefficient since they rely on light being reflected from room fabrics. This places a greater importance on the room decor and reflectance values.

21.6.2.4 Luminaire materials

The materials from which luminaires are constructed typically include metals, glass and plastic. Glass had been used extensively in earlier luminaires but has largely been replaced by plastics, except for some specialist applications e.g. where the light source produces excesses of heat, in which case glass is preferred from a safety viewpoint. Furthermore glass still finds use in situations where there is the likelihood of physical damage to the luminaire, since glass will be more robust.

Two types of glass are in common use for the manufacture of the bowls of luminaires i.e. borosilicate glass which can withstand high working temperatures and soda-lime glass. Both of these types of glass have to be subjected to toughening processes in order to provide additional

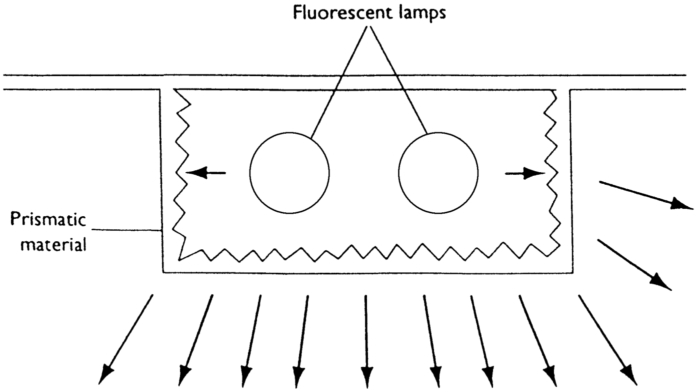


Figure 21.34 Light control by refraction

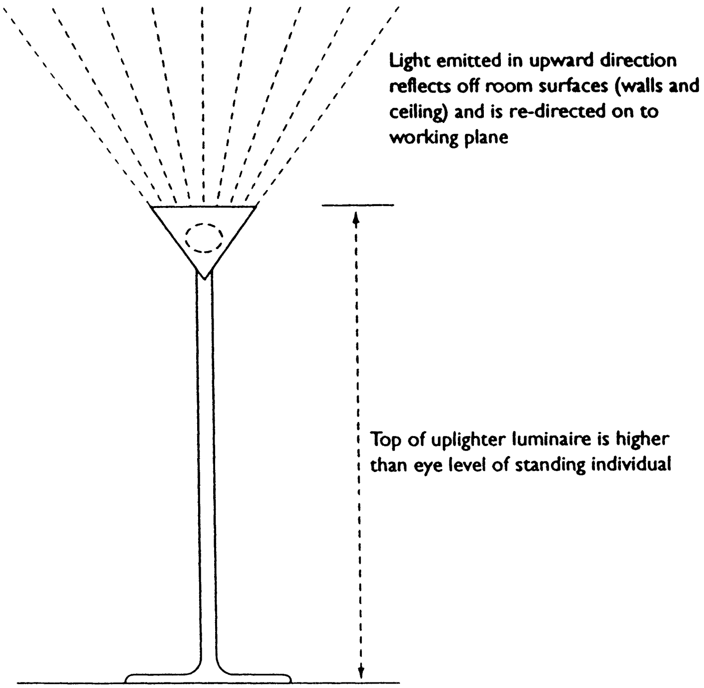


Figure 21.35 Principle of uplighter luminaire

protection if they are likely to be installed and operated in environments where there are rapid temperature variations.

Plastics, which are either thermosetting or thermoplastic, find their main use in the construction of diffusers. Polystyrene, acrylic and polycarbonate are used for diffusers. Polycarbonate, which is used in the manufacture of some types of safety spectacles, has a greater impact resistance than acrylic although both materials have been used for the construction of enclosures for use in areas where the luminaires are subjected to acts of vandalism. A form of plastic known as glass-reinforced plastic (GRP) is often used for luminaire canopies.

21.6.2.5 Mechanical strength of luminaires

Mechanical characteristics of luminaires include strength, windage resistance and resistance to vibration.

Luminaires must be capable of operating safely and efficiently within the environments in which they are expected to be installed. If they are operating in external environments they are likely to be subjected to meteorological factors such as wind, ice, snow all of which must be taken into account when considering the construction of the luminaires. Luminaires subjected to strong winds may also suffer the effects of vibrational oscillations that may lead to adverse operation.

21.7 Design techniques

The majority of industrial and commercial lighting problems are solved by the use of general lighting. One method of calculating the illuminance derived from a lighting system is known as the 'Lumen' method. Details of this are given below, procedure being grouped into logical steps.

Step 1: Illuminance Illumination values for various tasks are set out in the CIBSE Code for Interior Lighting.

Step 2: Luminaire type Consideration must be paid to all relevant factors, i.e. horizontal and vertical illumination requirements, glare prevention, efficiency, appearance, maintenance, economy, etc. For example, ordinary assembly work requires a certain amount of shadow to enable shape to be distinguished easily; therefore indirect lighting would be inappropriate, apart altogether from its relatively high running costs. The obvious choice for this class of work is the dispersive type of reflector.

Step 3: Mounting height The mounting height of fittings is usually dictated by the building construction, but, in general, it is advisable to make the height as great as possible compatible with good maintenance and installation facilities.

Step 4: Room reflectance It is now necessary to calculate, measure (or estimate) the effective reflectances of the three main room surfaces: (1) *the ceiling cavity* (area above the luminaires); (2) *the walls* (from the height of the working plane to the height of the luminaires); and (3) *the floor cavity* (area below the working plane).

Step 5: Room index From the room dimensions is calculated the 'room index' (RI), i.e. the ratio between twice the floor area and the area of the walls measured as the area between the working plane and the luminaires, i.e.

$$\mathrm{RI} = (L \times W)/[(L + W) \times H] \Leftarrow$$

where L and W are the room length and width, and H is the mounting height. Results may be rounded to the nearest value in the series 0.75, 1.25, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0. A room in which L and W are many times greater than H will have a high room index, while if L and W are less than H, it will have a low room index. It is important to realise that the room index is a measure of the relative, not the absolute, dimensions of the room.

Step 6: Utilisation factor and number of luminaires The room index affects the utilisation factor. The larger the room index, the higher the percentage of light reaching the working place. The utilisation factor will also be affected by the reflectances. The higher the room reflectances, the more light will be inter-reflected around the room. Utilisation factors are provided for different combinations of room reflectance and room index. In more recent publications utilisation factors (UF) may have the letters F, W or C in parentheses to indicate whether they refer to the floor, walls or ceiling, respectively, although normally only UF(F) values are published.

Table 21.4 gives an example of standard utilisation factors used in lighting calculations.

Allowance must be made for depreciation in light due to dust and dirt on fittings and surroundings: this is in the form of a maintenance factor. For normal interiors the factor is typically 0.8; for dirty locations it may be as low as 0.4.

For installations in high-bay foundries it may be necessary to make additional allowance for light absorption due to dirt and smoke. The average illuminance $E(\mathrm{F})$ over the working plane is given by

$$E(\mathrm{F}) = [\mathrm{UF(F)} \times n \times N \times \Phi \times \mathrm{MF} \times \mathrm{CF}]/A$$

where UF(F) is the utilisation factor for the reference surface S, N is the total number of luminaires in the installation, Φ is the light flux of each lamp (bare), MF is the maintenance factor of the installation, CF is the product of any additional correction factors necessary, n is the number of lamps per luminaire, and A is the area of the working plane.

Alternatively, the number of luminaires required is

$$N = [E(\mathrm{F}) \times A]/[\mathrm{UF(F)} \times n \times \Phi \times \mathrm{MF} \times \mathrm{CF}] \Leftarrow$$

Step 7: Spacing of luminaires and layout For a regular array of luminaires, $\mathrm{SHR}_{\mathrm{max}}$ is the maximum spacing/height ratio that will provide acceptable uniformity. When non-symmetric luminaires are used in long continuous runs, the maximum transverse spacing can be increased to $\mathrm{SHR}_{\mathrm{max,tr}}$. In addition to these limits the sum of the transverse

Table 21.4 Example of a standard utilisation factor (UF(F)) table for $\mathrm{SHR}_{\mathrm{nom}} = 1.5$

Room reflectance			*Room index*								
C	*W*	*F*	*0.75*	*1.00*	*1.25*	*1.50*	*2.00*	*2.50*	*3.00*	*4.00*	*5.00*
0.70	0.50	0.20	0.43	0.49	0.55	0.60	0.66	0.71	0.75	0.80	0.83
	0.30		0.35	0.41	0.47	0.52	0.59	0.65	0.69	0.75	0.78
	0.10		0.29	0.35	0.41	0.46	0.53	0.59	0.63	0.70	0.74
0.50	0.50	0.20	0.38	0.44	0.49	0.53	0.59	0.63	0.66	0.70	0.73
	0.30		0.31	0.37	0.42	0.46	0.53	0.58	0.61	0.66	0.70
	0.10		0.27	0.32	0.37	0.41	0.48	0.53	0.57	0.62	0.66
0.30	0.50	0.20	0.30	0.37	0.41	0.45	0.52	0.57	0.60	0.65	0.69
	0.30		0.28	0.33	0.38	0.41	0.47	0.51	0.54	0.59	0.62
	0.10		0.24	0.29	0.34	0.37	0.43	0.48	0.51	0.56	0.59
0.00	0.00	0.00	0.19	0.23	0.27	0.30	0.35	0.39	0.42	0.46	0.48

Rating: 65 W, 1500 mm.
Mounted: on ceiling.
Multiply UF values by service correction factors.

and axial SHR values should not exceed twice SHR_{max}. If SHR_{max} is not given, it can not be assumed to be greater than SHR_{nom} (the value for which the UF table is calculated).

SHR_{max} and $SHR_{max,tr}$ provide information only about the maximum spacing/height ratio that will result in acceptable uniformity on the horizontal working plane. In practical installations, obstructions or other factors frequently make closer spacing essential.

The spacing of units is limited by the mounting height, building structure and plant layout. In all cases it is recommended that spacing/height ratios (issued by the luminaire manufacturers) be not exceeded if even illumination is desired. Where freedom from shadow is required, closer spacings should be used. In calculating spacings it should be remembered that the mounting height should be taken from the working plane, be it the floor, a desk at 0.85 m or a work bench at 1.0 m.

Ceiling divisions, columns, shafting, ventilation trunking and other obstructions restrict possible layouts of outlets. It is thus desirable to draw a scale plan of the area showing all obstructions and plan the layout on this. In multistorey buildings the units should form, if possible, a symmetrical layout in the ceiling panels formed by the joints.

Especially where fluorescent lighting is concerned, the use of continuous trunking from which the luminaires can be suspended and which carries the wiring should usually be considered, as in many cases it can effect considerable economies in installation cost.

Where work benches or machines are located along the outer walls, the distance between the outside rows of luminaires and walls should not exceed one-third of the nominal spacing distance. If the wall space is a non-working area, this distance can be increased to one-half the nominal spacing. This should not be exceeded, as it is desirable to have a certain amount of light thrown upon the walls in order to maintain a reasonable brightness throughout the room.

Plant layout may determine the location of outlets, as in the case of the textile industry. Localised general systems are installed in such cases, the outlets being localised in relation to the plant.

An installation will not be satisfactory if the maximum spacing/height ratio is exceeded. Conformity, however, will still be unsatisfactory if there are obstructions (such as large machines); closer spacing is then essential.

21.7.1 Lighting systems

It is possible to categorise interior lighting into general lighting, localised lighting or local lighting:

General lighting A general lighting system is one that attempts to provide a constant illuminance across a working plane in an interior. It is however extremely unlikely that a uniform level of illuminance will be produced at all points across a horizontal working plane.

It has to be appreciated that general lighting does not take into account the visual tasks likely to be undertaken in an interior. This can have both advantages and disadvantages. One advantage is that it allows a degree of flexibility when locating individual areas within an interior where visual tasks can be carried out. A disadvantage of general lighting is that such systems can be very wasteful of energy since some areas within an interior are illuminated to a level greater than that required.

Localised lighting Localised lighting systems usually provide a required illuminance on the work areas in combination with a reduced level of illuminance in non-working areas, for example walkways. An often-used example of this is found in open plan offices where workstations are lit using uplighters. Simultaneously walkways and other non-work areas are lit by means of a number of ceiling-mounted downlighters. It will be evident that this system is correspondingly less wasteful of energy than the general lighting system.

Local lighting Local lighting systems provide illuminance over a relatively small area in which the visual task is located. It is often used in combination with general lighting so that together the local lighting and general lighting will produce the required illuminance on, and surrounding, the visual tasks.

Figure 21.36 shows the differences between the types of lighting system described.

21.7.2 Lighting surveys

Lighting surveys are often undertaken in response to adverse criticism from workers who complain that the lighting in their workplace is in some way unsuitable and/or insufficient. Whilst such an allegation may sometimes be justified, it is often the case that in an environment where there are reported visual problems the cause is non-lighting in origin.

Such non-lighting influences on the visual environment must therefore be investigated before any decision is taken to implement a full lighting survey. Typical non-lighting causes include:

(a) changes in the condition of the decor, e.g. room fabrics have become dirty and their corresponding reflectance values have decreased;
(b) changes in condition of fenestration e.g. windows have become dirty and therefore the transmission of natural daylight to the room interior will be impeded;
(c) changes in layout of the interior e.g. workstations have been repositioned;
(d) changes in working practices and activities.

21.7.2.1 Instrumentation

The major parameters of interest likely to be considered in a lighting survey include illuminance, luminance, reflectance and daylight factor. Equipment is available which is capable of displaying, either in analogue or digital form, more than one of the parameters listed.

21.7.2.2 Illuminance measuring equipment

Such instruments typically incorporate a selenium or silicon photovoltaic cell. The specification of the instruments typically includes details of spectral response, angular response, linearity of response and operational characteristics of instruments in adverse temperature conditions.

The spectral response of the cells typically used in the construction of illuminance measuring instruments will differ from the response of the human visual system. It is therefore necessary to correct for this differential by applying some form of compensation. This is often achieved by using filters and when such filters are incorporated into an instrument, the device is referred to as colour corrected.

The magnitude of illuminance recorded by, and displayed on, an instrument is influenced by the cosine of the angle the incident ray subtends with the normal to the plane of the instrument detector. It is necessary therefore to apply

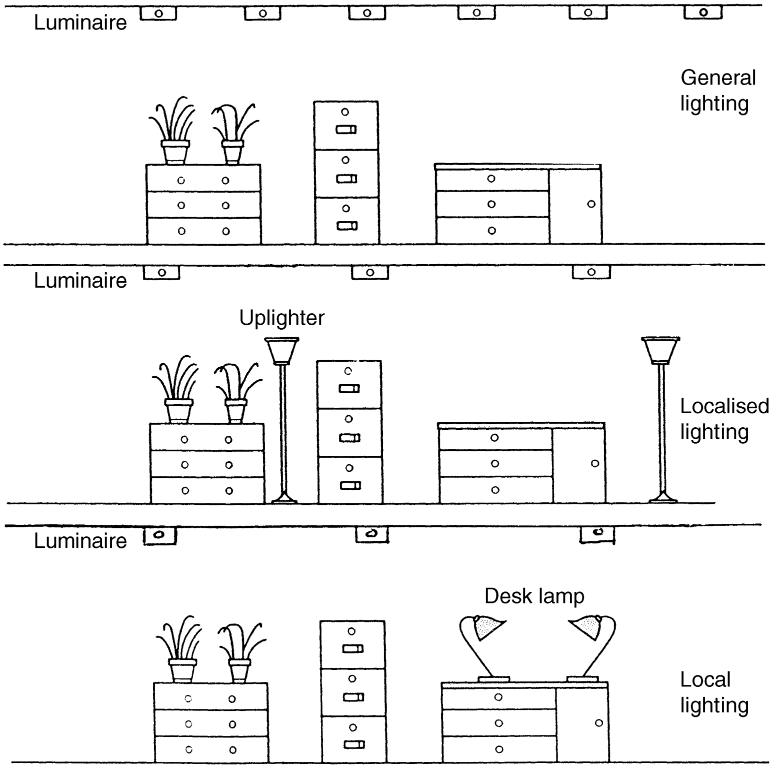


Figure 21.36 Types of lighting system

some form of compensation that takes into account the direction of the incident light falling upon the light-sensing detector. Instruments, which are capable of measuring illuminance values accurately from any incident direction, are referred to as cosine corrected.

The electronic components incorporated into the device will influence the linearity of response of the measuring equipment and the equipment may also be affected by adverse temperature conditions.

21.7.2.3 Luminance measuring equipment

Luminance measuring instruments incorporate photovoltaic cells, which also require to be colour corrected, and which are required to have a linear response.

21.8 Lighting applications

21.8.1 Office and interior lighting

It is possible to classify the main requirements for optimum lighting conditions within interiors as:

(a) health and safety;
(b) visual performance;
(c) aesthetics; and
(d) personal comfort.

When striving to obtain an office environment, which is both aesthetically pleasing and acceptable to the eye, it is usual to include:

(a) an analysis of those visual tasks that are likely to be encountered within an office;
(b) a balance between the quantity of daylight entering an office interior and the corresponding requirements from artificial lighting;
(c) a balance between direct and diffuse lighting contributions so that where practical no adverse three-dimensional and/or modelling effects will be produced;
(d) the provision of an environment that is free from both glare and any associated distractions.

When considering the health and safety of personnel, office lighting should ideally allow room occupants to carry out their normal duties in a manner that, under normal conditions, is considered to be safe. The lighting provided must not, under any circumstances, place any occupants of the room at risk. Furthermore it is necessary to provide for the safety of occupants in the event of an essential evacuation of the premises. In the United Kingdom emergency lighting is a requirement under The Building Regulations and is covered by BS 5266 Emergency Lighting.

It is important not to overlook both aesthetics and personal comfort when considering optimum office lighting conditions. There is a psychological influence on the occupants of an interior caused by the decor and room appearance and subsequently this is likely to have a 'knock on' effect upon worker behaviour that will ultimately affect output productivity.

21.8.1.1 Sick building syndrome and building related illness

The term sick building syndrome (SBS) is used to describe a host of symptoms which appear to have a high incidence in some buildings and which have a definite work relationship. It is essential to distinguish between sick building syndrome and other illnesses, which are connected with buildings, or building services. These building related illnesses are typically much less common; they almost always have a clearly identifiable microbiological cause and usually affect relatively few occupants. The term building related illness (BRI) is often preferred for such conditions as humidifier fever and Legionnaire's disease.

Sick building syndrome (SBS) can be caused by a host of factors, one of which is lighting. The symptoms of sick building syndrome (SBS) include headaches, nausea, dizziness, irritation of eyes, nose and throat and general lethargy.

21.8.2 Factory lighting

Typical outdoor lighting installations at factories include general external yard lighting, loading bays and storage areas.

The objective for factory roadway lighting is to provide suitable and sufficient illumination so as to allow the safe passage of personnel both on foot and in vehicles. To this end care must be taken when designing a lighting installation for such areas in order to provide the required illuminance but simultaneously to avoid the development of glare being experienced by works' personnel. It is normal to monitor and control values of average illuminance and point illuminance and in so doing maintain acceptable values of uniformity ratio so as to avoid producing 'patchy' lighting.

Loading bays and storage areas require special attention including due consideration given to the elimination of shadows.

21.8.3 Security lighting

The aims and objectives of security lighting are:

(a) to improve the likelihood of detection, identification and apprehension of intruders;
(b) to improve the efficiency of other security measures in use;
(c) to improve safety levels for authorised personnel.

Owners of shops will be concerned with the security of their premises especially where the sales rooms and associated areas contain stock, which could be of considerable financial value. It will be evident that in such situations the security lighting should pay particular attention to those areas where routine entry to the premises is gained, in addition to those areas of the interior that are visible externally.

Any lighting provided in the loading area will not only assist with the security of the premises but will also help with the normal operations of authorised personnel within the boundary of the premises.

One of the main considerations when contemplating the security lighting requirement for offices is the size of the premises. With a small suite of offices or a single lock-up office it is difficult to justify the use of dedicated security personnel. Conversely the situation applying with larger office blocks often demands the use of security guards whose sole function is to patrol and guard the offices.

Factories or larger scale premises will create different problems. In addition to the theft of finished goods raw materials are also targets for criminals and the security of such premises must therefore, of necessity, commence at the factory gatehouse or main entrance.

When designing a security lighting installation it is essential to avoid the production of shadows. In addition to posing a danger for authorised workers on a site, shadows are likely to provide areas in which criminals are likely to remain undetected and from which they can therefore subsequently make good an escape.

21.8.4 Floodlighting

Floodlighting can be applied to many installations e.g. buildings, industrial premises and for sport.

Floodlit buildings are commonplace in town and city centres. Thoughtful siting of luminaires and careful selection of the types of light sources used can produce a floodlit effect which is both striking and pleasing to the eye. It is however important to appreciate that floodlighting is not a procedure for illuminating a building during the hours of darkness to the same luminance level, and in the same manner, as that provided by natural daylight.

For optimum floodlighting of buildings there should be a flow of light across the front of a building. The direction of this flow should not be identical to that of the direction of normal viewing of the building front. Any contravention of this recommendation will lead to an absence of shadows producing a building appearance that is seen to lack character.

It will be evident that the colour output of the light source(s) used in any floodlighting scheme is critical, and the deliberate production of a colour difference can be used to advantage in the process of highlighting different areas of a building.

Industrial floodlighting is a necessary commodity for those locations where outside work continues during the hours of darkness. Adequate lighting of the correct type will ensure that maximum benefit is obtained from external work activities. Suitable and sufficient working illuminance combined with effective glare control should enable visual task details to be detected clearly, concisely and with speed which should subsequently allow work to proceed with safety and without creating visual problems for the workforce.

In many industrial activities it is essential to be able to discern the surface colour of engineering and production materials and it will be evident that floodlighting contributes markedly to the ease with which this identification process is carried out. In such situations those light sources with poor colour rendering properties are totally unsuitable and examples of such light sources include low pressure sodium lamps.

Sports floodlighting incorporates luminaires mounted on towers or grandstand fasciae. Light sources must have good colour rendering properties in particular when colour television transmission of events is likely.

21.8.5 Public lighting

Public lighting can be defined as any lighting provided for the public use, which is usually maintained at the public's expense. The functions of public lighting can be classified as:

(a) to ensure the continued safety of road users and pedestrians;
(b) to assist the police in the enforcement of the law;
(c) to improve the environment for the benefit of residents; and
(d) to highlight shopping areas and areas of civic importance.

When a driver is travelling along a road during the hours of darkness, objects are seen by one of two processes, either (a) direct vision (using surface detail) or (b) by silhouette vision. A driver will see as silhouettes either small objects at medium distances or large objects at greater distances. By directing the beams from the vehicle headlights on to the road so that they strike it at glancing angles (towards oncoming motorists) the whole of a road surface can be made to appear bright.

For optimum road lighting conditions the designer should strive for the following:

(a) a uniform road surface luminance;
(b) adequate and acceptable illuminance;
(c) suitable silhouette contrasts of the road ahead; and
(d) glare control from road lighting luminaires.

Low pressure sodium lamps have the highest luminous efficacy of artificial light sources and have been used extensively for road lighting. Their colour rendering properties are very poor and many public lighting engineers use such monochromatic sources only for minor road lighting installations. High pressure sodium lighting is now used on many trunk roads, other major roads and in town centres and areas of civic importance.

21.8.6 Light pollution

Extraneous light, in various forms, is a public enemy of increasing proportions. Astronomers are often particularly aggrieved in respect of this offensive light insomuch as they would prefer to view the night sky with as little stray light as possible. The situation occurs for a variety of reasons but in general terms it is due to either badly designed lighting installations or inaccurately aimed luminaires or a combination of both.

The likely consequences are sky glow or light pollution, where artificial lighting spills over, and therefore trespasses into, areas for which it is not intended. The situation becomes more pronounced when light is scattered through the night sky by particles of dust and droplets of water.

There appears little doubt that light pollution is a serious problem and unless the situation is addressed and subsequently reversed there is every possibility that the view of the night sky and all of the details contained therein, will be lost.