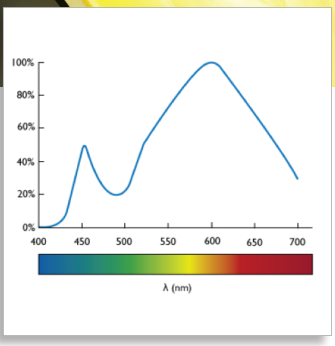


# Lighting Hardware

LAMPS

GEAR

LUMINAIRES

CONTROLS

Wout van Bommel
Abdo Rouhana

PHILIPS

sense and simplicity

# Preface

The subject of this, the second in a series of course books, is Lighting Hardware. A knowledge of lighting hardware is the basis for success in the commercial, technical and design professions in the lighting business. In order to guarantee the best solutions for the end-users of light, we have to follow developments both in conventional and in completely new types of light sources, such as the solid-state light source, or LED. This is why in this book all light sources are dealt with, ranging from incandescent and halogen lamps to the modern gas discharge lamps and to the most recent solid-state light sources: the LEDs and OLEDS.

Most lamps need auxiliary devices such as ballasts, igniters and drivers for their correct operation. To be able to control, market, and use these devices - also referred to as electrical gear - a good understanding of both conventional and electronic systems is needed.

Whilst the lamp-gear combination can be seen as the starting point of a lighting installation, it is the luminaires in which they are housed that determine precisely how and how efficiently the light is brought to where it is needed, and how it is prevented from reaching places where it is not wanted. At the same time, the luminaire is also invariably the most visible part of the lighting installation and so is also very important from an aesthetic point of view. The required luminaire characteristics vary greatly depending on the lighting application, such as indoor general lighting, indoor accent lighting, road lighting, and floodlighting. An insight will therefore be provided into the desired luminaire characteristics for all these different categories.

Lighting control systems can minimize the energy consumption and maintenance costs and maximize the life of lighting installations. Where, in the past, automated control systems were expensive and complicated, today they are much simpler and very cost effective. It is for this reason that they are becoming an ever-more integral part of many lighting installation. The fundamentals of practical lighting control systems are dealt with in the last chapter of this book.

All subjects are dealt with as simply as possible. For the more advanced reader some of the more complicated mathematics, physics and electronics are given as footnotes or in special text frames.

The first book of this series of course books is entitled: *The theory of light and lighting.*

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Take the lead in light

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# Table of Contents

# 1 Basics of lamps

### 1.1 Lamp types

Lamps are of three fundamentally different types:

- thermal radiators
- gas discharge radiators
- solid-state radiators

Both normal incandescent and halogen incandescent lamps belong to the group of thermal radiators. Gas discharge lamps are available in high and low-pressure versions and use either mercury or sodium as their main gas component. Solid-state light sources are produced from semiconductor material. Those produced from inorganic semiconductor material are called LEDs, while those produced from organic material are called OLEDs. In the Book "Theory of Light and Lighting" in this series of course books, the basic operation principles of these technologies have been explained. Fig 1.1 groups the various Philips type of lamps according to their technology.

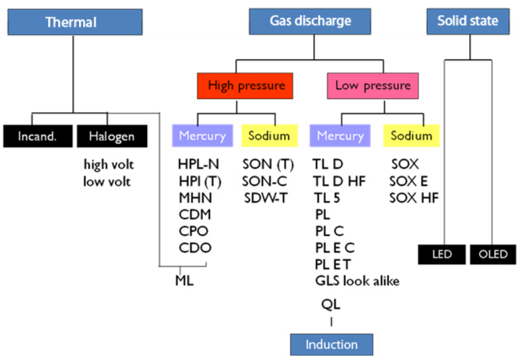



Fig.1.1. Lamp types, indicated with Philips name, listed under their family group name.

Lamp types with a relatively high light output and thus with high luminous intensities are often referred to as High Intensity Discharge or HID lamps. Low and high-pressure sodium lamps, high-pressure mercury lamps (including metal halide lamps HPI, MHD, MHN and CDM) together form this HID group.

### 1.2 Performance characteristics

The catalogue of a lamp manufacturer lists a great number of different lamp types. The reason for this is that the ideal lamp simply does not exist. A lamp that is suitable for one application may be totally unsuited for another application. In other words, each lighting application calls for a lamp with a specific set of properties. Table 2.1 provides a description of some of the more important lamp properties, which can vary with different lamp types. It is the task of the lighting designer to choose the lamp properties best suited to a particular application

| | |
|---|---|
| Light output | Price |
| Efficacy | Shape and dimensions |
| Light colour | Weight |
| Colour rendering | Brightness |
| Lifetime | lamp temperature |
| Light depreciation | Temperature |
| Ballast yes / no | sensitivity |
| Ignitor yes / no | Burning position |
| Built-in optics yes / no | Run-up time |
| | Environment- |
| | unfriendly materials |

Table 2.1 Some of the more important properties of lamps.

In this Section the definition of the more important lamp properties will be given and explained. In later Chapters that deal with the different types of light sources, detailed values of the properties will be given.

#### 1.2.1 Luminous efficacy

The ratio between the luminous flux (output) of a lamp and the power dissipated in that lamp is termed its "luminous efficacy" and is expressed lumen per watt (lm/W). It is a measure of how energy efficient the light is produced. Values range from approximately 10 lm/W for an incandescent lamp to 100 lm/W for a fluorescent tube and 190 lm/W for a low-pressure sodium lamp. With most lamp types the luminous efficacy increases with an increase of lamp power.

In the case of gas discharge lamps, the ballast required to limit the current through the lamp for its proper functioning also consumes energy. Therefore, when stating the luminous efficacy values for these lamps, the energy consumption of the ballast should, be taken into account. The official expression is "system luminous efficacy". In this book we do this based on optimised ballasts for the lamps in question.

Since 1998, a European directive requires that all household lamps marketed in Europe have an energy label as shown in Fig. 1.2, where the energy efficiency, and thus the luminous efficacy, improves from G to A.

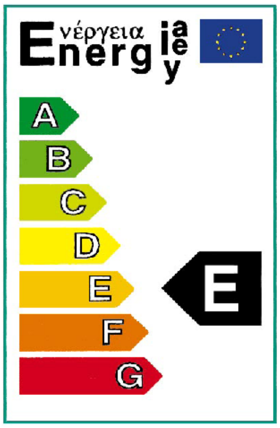



Fig. 1.2 EU Energy label for household lamps.

### 1.2.2 Lumen package

Each lamp type must be available in versions with different lumen outputs (different lumen packages) in order to be able to create different lighting levels with each lamp type. This is the reason why, for example, GLS incandescent lamps are available in different wattages corresponding to different lumen packages. Most lamp types cover only part of the lumen range. For example, incandescent and fluorescent lamps are available in the lower lumen-package range: for normal incandescent lamps up to some 1500 lumen (corresponding to 100 W to 150 W) and for common types of fluorescent tubes up to some 6000 lumen. On the other hand, some metal halide lamp versions are available in lumen packages of up to more than 200 000 lumen. The lumen-package range of a lamp type is one of the aspects that determine in which applications that lamp type can be employed.[1]

### 1.2.3 Colour temperature

In the book “Theory of light and lighting” of this same series the concept of (correlated) colour temperature has been explained in some detail (Chapters 2 and 6).

The colour temperature is used to characterise the different types of white light of incandescent lamps, discharge lamps (formally correlated colour temperature, CCT), and solid-state light sources (again, formally, correlated colour temperature). Lamps with high colour temperatures give cool white light (relatively much blue in the light) while lamps with low colour temperatures give warm-white light (relatively more red in the light). As an example, incandescent lamps have a colour temperature of around 2700 K to 2800 K whereas neutral-white fluorescent tubes have a colour temperature of some 4000 K.

The (correlated) colour temperature CCT, expressed in Kelvin (K), should be given by the lamp manufacturer. It is calculated from the spectral power distribution of the lamp.

### 1.2.4 Colour rendering

In the book “Theory of light and lighting” of this same series the concept of colour rendering index has been explained (Chapter 6).

Colour rendering is the ability of light to reproduce (render) faithfully the colours of objects. Light sources with a continuous spectrum do this better than light sources with a discontinuous spectrum. In order to be able to rank light sources according to their colour-rendering capabilities, the International Lighting Commission CIE introduced the “general colour rendering index” Ra. This index is based on the appearance of eight standardised colours illuminated by the light source in question, compared to their appearance under a reference light source. The colour-rendering index thus represents the average colour shift of these eight standardised colours. If there is no shift at all, as is the case with light sources having a continuous spectrum (viz. all thermal radiators), the value of Ra equals 100. If all colours disappear completely, as in the case with low-pressure sodium light, Ra equals zero. The colour-rendering index Ra of a lamp is obtained from the spectral power distribution of that lamp. For example, Ra is 100 for incandescent lamps, 80 for 840-type fluorescent lamps, and zero for low-pressure sodium lamps..

### 1.2.5 Lifetime

It is impossible to predict the end-of-life of individual lamps because of the great many factors that govern their lifetime. Sensible lifetime definitions have to be based on a large batch of lamps of the same type, taking their statistical variation in end-of-life into account.

#### Average life

Average life, sometimes also called average rated life, is defined as the time after which 50 per cent of lamps in a large representative batch, tested under controlled operating conditions (as defined by the International Electrotechnical Commission IEC), have failed. Results of these tests are published by lamp manufacturers as mortality curves. Fig. 1.3 shows the life mortality curves of two different types of gas discharge lamps. The grey areas are an indication for the spread that may be expected. One curve corresponds to a lamp type having an average life of 20 000 h and the other to a lamp type with an average

1 The initial luminous flux of a gas discharge lamp is defined by its value measured after 100 burning hours, when its performance characteristics have become stable.

life of 12 000 h. As a comparison, incandescent lamps (General Lighting Service types) have typical average-life values of 1000 h.

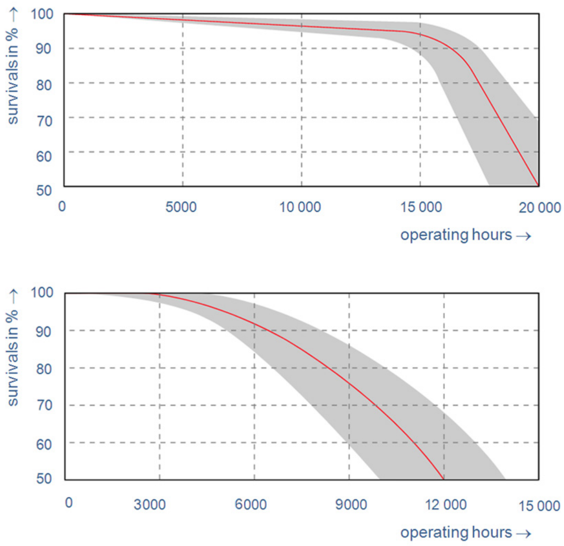



Fig. 1.3 Examples of mortality curves of two different types of gas discharge lamp.

### Economic life

For the owner of the lighting installation, the concept of average rated lamp lifetime is only of limited importance. More relevant is how long the installation will continue to provide lighting up to specification in an efficient way. As will be discussed in Section 1.2.6 in more detail, the light output of all lamp types declines gradually during operation. We call this lamp-lumen depreciation. The overall result is a decrease in luminous efficacy and a decrease in lighting level, which may reach a stage where it is economically more profitable to replace the lamp by a new one, rather than to wait for its ultimate failure. The concept of economic lifetime has therefore been introduced. It takes not only lamp failure into account, but also lamp lumen depreciation.[2] The economic life of lamps in an installation is defined as: *the time after which, due to lamp failure and depreciation of light output of the lamps, the light output of the installation has fallen by a certain percentage*. This point can be predicted if both the mortality and depreciation curves for the lamp type considered are available. Which percentage is relevant is especially dependent upon the type of application and the actual costs of lamp replacement (including labour cost). For outdoor installations, a percentage of 30 per cent is often considered acceptable, while for indoor installations with fluorescent lamps a value of 20 per cent is more common. The corresponding economic lifetimes are called $L_{70}$ and $L_{80}$ respectively, 70 and 80 standing for the percentage of light that remains. For fluorescent lamp types (high-quality phosphors), $L_{80}$ would mean something like 17 000 h economic lifetime (10 per cent lumen depreciation and 10 per cent mortality). If, at the end of their economic life all the lamps are replaced in one go (group replacement), the need for individual lamp replacement (spot replacement) because of early failures is limited. Since individual spot replacement is often expensive, the overall cost for maintaining a lighting installation can thus be limited.

2 In some countries the expression "service life" is used instead of "economic life".

## 1.2.6 Lamp-lumen depreciation

The light output of virtually all lamp types declines gradually during operation. The causes of light output depreciation are numerous. With incandescent lamps it is especially the blackening of the bulb – caused by evaporation of the filament. Discharge lamps also suffer from blackening, in this case due to scattering of the electrode material, which settles on the wall of the discharge tube. With fluorescent lamps and high-pressure mercury lamps with a fluorescent coating, the major cause of light output depreciation is a gradual exhaustion of the fluorescent powder, which slowly loses its effectiveness. The result is not only a decrease in light output, but often a change in light colour as well – although present-day phosphors are much more stable than those used previously.

An example of the lumen depreciation of a fluorescent lamp equipped with different types of phosphor coatings is shown in Fig. 1.4. These types of lumen depreciation curves can be provided by the lamp manufacturers for all their different lamp types.

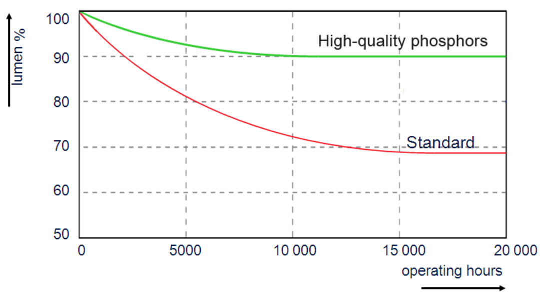



Fig. 1.4 Typical lumen depreciation curves for fluorescent lamps.

## 1.2.7 Lamp price

Needless to say, in the process of deciding which lamp is best suited for a given situation, the lamp price plays an important role. But it is not only the initial lamp price or initial investment cost that should be taken into account, for the running cost of the installation is the determining factor (amortization of the installation, energy cost and lamp replacement cost). This means that in choosing a lamp type for a certain situation, the initial lamp price (or installation price) should be balanced against the energy efficiency and the economic lifetime of the lamp.

It is difficult to give absolute lamp prices in a book such as this, because lamp prices vary from country to country and with time. We will therefore indicate lamp prices relative to the price of a simple GLS incandescent lamp. As we will see later, the relative price expressed in this manner varies between 1 (for GLS) and some 150 (for some types of metal-halide lamp).

### 1.2.8 Burning position

Some halogen lamps (those with long filaments) and some gas discharge lamps are restricted as to their burning position. The reason for this is sagging of the filament, soiling of the electrodes by particles (e.g. sodium or mercury particles), or disturbance of the thermal balance of the lamp. Failure to respect the correct burning position results in ignition problems, colour shift and a shorter lifetime. Where relevant, permissible burning positions are given in lamp documentation sheets or on lamp packaging (Fig. 1.5).

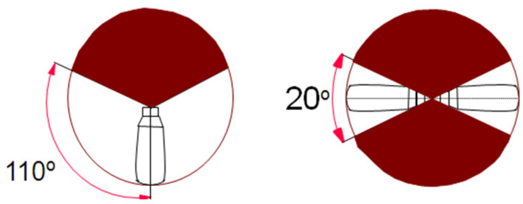



Fig. 1.5 Two examples of permissible burning positions of lamps..

### 1.2.9 Run-up time

Incandescent lamps and solid-state light sources reach their full light output immediately after switch-on. Gas discharge lamps containing metallic vapour, such as mercury or sodium, need a warm-up time to enable the metals to vaporise to a stable condition. The full light output is only gradually reached during this process. The time needed from the moment of switch-on until the lamp reaches its full light output is called the run-up time. Fluorescent lamps have short run-up times of less (sometimes much less) than a minute. Other discharge lamps may have run-up times of a few minutes up to, in the case of low-pressure sodium, 15 minutes.

### 1.2.10 Re-ignition time

If incandescent lamps and solid-state light sources are switched off, they restart immediately when switched on again. Some gas discharge lamps need some time after switch-off to cool down so that the vapour pressure can decrease sufficiently before the lamp can again be restarted. This so-called re-ignition time is dependent on the type of gas discharge lamp and the starting device (igniter) used. Re-ignition time may vary from half a minute to several minutes, and even up to around 15 minutes in the case of some metal-halide lamps.

### 1.2.11 Dimming

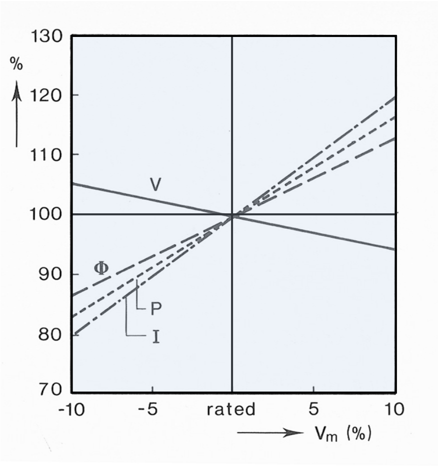
Incandescent lamps and halogen lamps can easily be dimmed from 100 per cent light output to zero per cent, for example by reducing the input voltage with a transformer. To dim these lamps in such a way that it also results in energy saving, requires the use of some more advanced, but readily-available equipment. Also, most solid-state light sources can easily be dimmed from 100 per cent light output to close to zero per cent. Some gas discharge lamps cannot be dimmed without considerable adverse effects on either lifetime or colour quality. Those that can be dimmed cannot always be dimmed over the full 100 to 0 per cent range.

### 1.2.12 Ambient-temperature sensitivity

The light characteristics of incandescent lamps are not dependent upon the ambient temperature in which the lamp is used. The light output of some gas discharge lamps, however, is influenced by the ambient temperature. This is the case, for example, with fluorescent lamps (both tubular and compact), where the light output drops sharply if used at an ambient temperature of less than 15°C. With solid-state light sources, unlike gas discharge lamps, the light output decreases with increasing ambient temperature and increases with decreasing ambient temperature. According to the International Electrotechnical Commission (IEC), the properties of light sources are usually specified for an ambient temperature of 25°C

### 1.2.13 Sensitivity to mains-voltage variations

Any variation from the nominal mains voltage causes changes in the operating characteristics of lamps. Lamp characteristics that are affected are: lamp voltage, lamp current and lamp power, and therefore also luminous output, luminous efficacy and lifetime. Sometimes, the type of ballast used plays a role as well. In some lamps, the colour quality of the light is also affected. Lamps usually function well enough if supply-voltage deviations remain within 5 per cent of the rated value. Lamp manufacturers supply information on the influence of mains-voltage variations in diagrams, such as is given, for example, in Fig. 1.6 for a fluorescent lamp and a low-pressure sodium lamp, respectively.



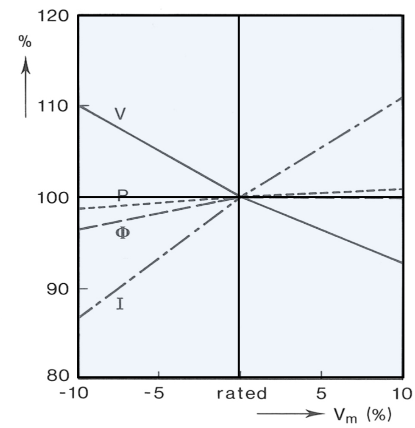




Fig. 1.6 The effect of mains-voltage variation on lamp voltage (V), lamp current (I), luminous flux (Ø) and lamp power (P) for a fluorescent tube with inductive ballast (top) and a for a low-pressure sodium lamp (bottom).

# 2 Incandescent lamps

There exists a wide variety of incandescent lamps, ranging from the most common types, viz. the General Lighting Service (GLS) lamps to reflector lamps, coloured lamps and halogen incandescent lamps. Given the special operating principle and construction of halogen incandescent lamps, these will be dealt with in a separate section (Section 3). The most important application area of normal incandescent lamps is home lighting. Because of the low efficacy and short lifetime of incandescent lamps, the more efficient and longer-life gas discharge and solid-state lamp alternatives have become increasingly more important for home lighting.

## 2.1 Operating principle

The operating principle of the incandescent lamp is extremely simple. An electric current is passed through a thin wire of comparatively high resistance so as to heat this to incandescence. The wire is usually heated to a temperature of between 2700 K and 2800 K, at which temperature it emits warm-white light. The wire is placed inside a glass bulb, which is either at a vacuum or contains an inert gas.

## 2.2 Lamp construction

The main parts of an incandescent lamp are (Fig. 2.1):

- glass bulb
- filament
- filament support – consisting of a glass stem, lead-in wires (also serving as a fuse) and support wires
- bulb fill gas
- lamp cap

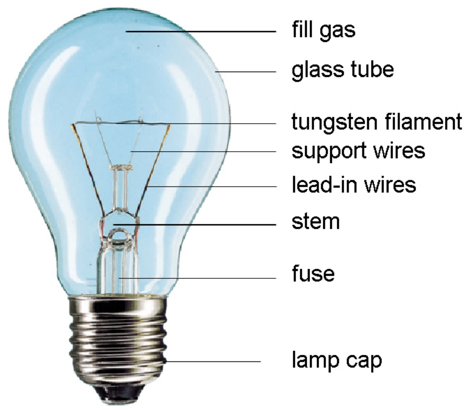



Fig. 2.1 The main parts of an incandescent lamp.

### 2.2.1 Filament

With very few exceptions, filaments for incandescent lamps are made of tungsten, a metal that has the advantage of a high melting point combined with a relatively-low vapour pressure, even at very high temperatures. This low vapour pressure means a low evaporation rate of the tungsten material and thus a relatively long life of the coil. The tungsten wire is generally wound into a single or double coil for reasons of compactness and heat conservation and concentration around the coil. The double coil (Figs 2.2 and 2.3), which conserves and concentrates the heat better than does a single coil, was patented in 1917. It was the last fundamental improvement of incandescent lamps as far as operating principle is concerned.

Fig. 2.2 Double-coiled tungsten wire (picture from 1917 patent)

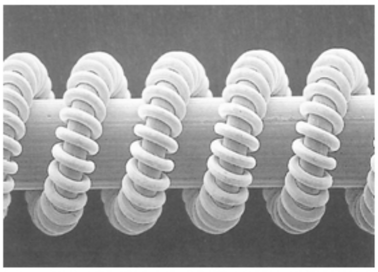


Fig. 2.3 Winding of the tungsten wire into a double coil around a core, which is removed later on in the manufacturing process.

### 2.2.2 Bulb

The bulbs of GLS lamps are made of soda-lime glass, the most common and cheapest type of glass available. For lamps that must withstand high temperatures or temperature chocks, more resistant glasses are used.

The bulb of an incandescent lamp can be of different sizes and may take different shapes, depending on the application. Also depending on the application, the bulb may undergo various treatments. The most commonly-employed treatments are (Fig. 2.4):

- **Frosting**: this is done by etching the inside of the bulb. The etching of the surface results in a satin finish and moderate diffusion of the light with hardly any reduction in transmittance.
- **Opalising**: this is achieved by coating the inside of the bulb with a special powder. It provides better diffusion of the light at the cost of slightly greater light absorption,.
- **Mirror-coating**: reflector lamps receive an internal mirror coating. Silver mirrors are produced by evaporation of aluminium under vacuum.

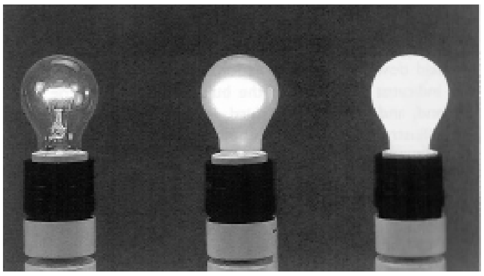


Fig. 2.4 Clear, frosted and opal GLS lamps.

### 2.2.3 Fill gas

Two types of incandescent lamp are available on the market; vacuum lamps and those with a fill gas. The great majority of incandescent lamps contain a fill gas, the main purpose of which is to reduce the evaporation rate of the filament and thus increase the lamp life. The fill gas is a mixture of argon and nitrogen. In incandescent car lamps, krypton is usually employed (it is more expensive, but results in a higher luminous efficacy).

Even small quantities of oxygen or water vapour could shorten the lifetime of the tungsten wire through corrosion. To remove even the slightest traces of these, a so-called "getter" is added. The getter absorbs oxygen and water.

### 2.2.4 Lamp cap

The lamp cap connects the lamp to the power-supply socket. There are two different standardised cap types: the screw cap (also called the Edison cap), and the bayonet cap (Fig 2.5). Both are employed in various sizes:

- Screw (Edison) type: IEC designation E10, E14, E27, E40
- Bayonet type: IEC designation B15, B22

The number indicates the diameter of the lamp cap in millimetres.

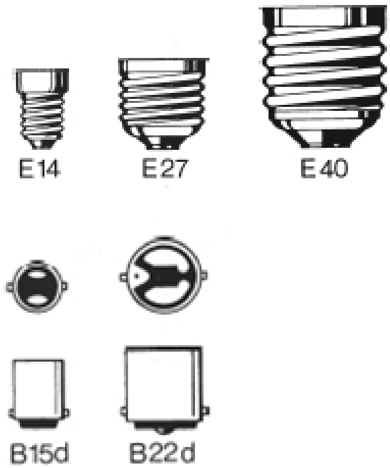



Fig. 2.5 Screw (Edison) and bayonet lamp caps with their IEC designation.

The United States uses different diameters of screw caps, which are identified by names, rather than by the IEC designation, these are:

- Candelabra (E12)
- Intermediate (E17)
- Medium (E26)
- Mogul (E39)

## 2.3 Performance characteristics

### 2.3.1 Energy balance

Fig 2.6 shows the energy balance of a 100 W GLS lamp. It shows that only approximately 8 per cent of the input power is emitted in the form of visible radiation. The rest is lost as heat (by conduction, convection and infrared radiation).

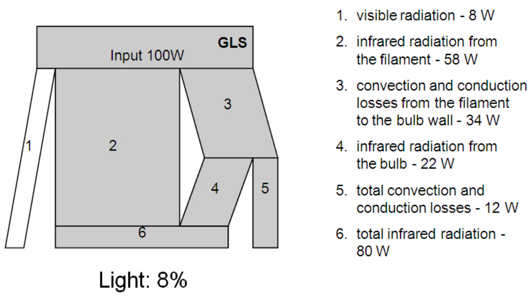



Fig. 2.6 Energy balance of a 100 W GLS lamp.

### 2.3.2 Luminous efficacy

The luminous efficacy of a standard GLS lamp varies, depending on its wattage, between 8 lm/W and 15 lm/W. For a standard 75 W lamp, the efficacy is around 12 lm/W. The lower the wattage, the lower the efficacy.

Compared with gas discharge and solid-state light sources, the efficacy of incandescent lamps is very low indeed. For reasons of sustainability, governments in some parts of the world (e.g. European Union), have taken the decision, or are considering taking the decision, to ban GLS incandescent lamps.

### 2.3.3 Lumen-package range

Common types of GLS lamps are available in the range from some 100 to 1500 lumen (corresponding wattage range approx. 15 W - 200 W). There are, of course, many special lamps with both lower and higher lumen packages: think, for example, of bicycle and torch lamps on the one hand and light-house lamps on the other.

### 2.3.4 Colour characteristics

Incandescent lamps have a continuous spectrum radiating more energy at longer wavelengths (red) than at shorter wavelengths (blue) (Fig. 2.7).

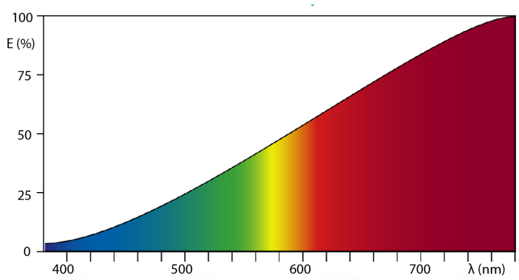



Fig. 2.7 Relative spectral energy distribution of an incandescent lamp.

Their colour rendering index is 100, and standard GLS lamps have a colour temperature of between 2700 K and 2800 K (warm-white light).

Coloured opal lamps for party or festive lighting are available, as are lamps producing a special tint of 'white' light (e.g. flame, terracotta, beige).

### 2.3.5 Lamp life

Lamp manufacturers can, in principle, balance the life of an incandescent lamp against its luminous efficacy: higher lifetime, lower efficacy. However, by international agreement, the lamp industry has standardised the average-rated-life of standard GLS lamp at 1000 hours (750 hours in the USA). Nevertheless, for special applications lamps are available where the balance between lifetime and efficacy is different. Examples are photo and film-studio lamps and torch bulbs on the one hand with their shorter life but higher efficacy (and higher colour temperature) and beacon lamps on the other with their longer life but lower efficacy.

### 2.3.6 Lamp-lumen depreciation

An important reason why the light output of an incandescent lamp decreases with time is that tungsten evaporates from the filament and settles on the bulb wall, blackening it. At the end of the rated average life (1000 h) the lumen depreciation can amount to as much as 15 to 25 per cent.

### 2.3.7 Run-up and re-ignition

Incandescent lamps give their full light output immediately after switch-on and after being switched off they re-ignite again immediately.

### 2.3.8 Switching

Frequent switching is not normally detrimental to lamp life, but when the filament has become critically thin through age, the mechanical strain caused by the rapid temperature change as a result of switching will be sufficient to cause its breakdown (Fig 2.8). This is the reason why incandescent lamps approaching the end of their life usually fail the moment they are switched on or off.

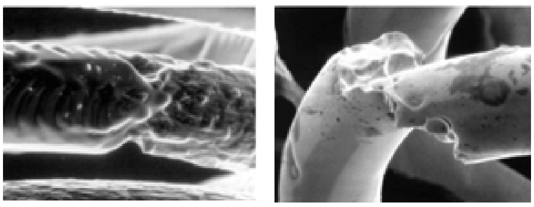


Fig. 2.8 Thin spot in the filament eventually resulting in breakage of the filament.

### 2.3.9 Dimming

Normal incandescent lamps can be dimmed without restriction. Dimming by reducing the supply voltage to the lamp with an adjustable resistance in series with the lamp is technically easy but does not result in energy saving. A relatively expensive adjustable transformer (potentiometer) results in energy saving, but not very much. Today the usual method to dim incandescent lamps is by thyristor dimmers that cut part of the AC current during each of the 50 (or in the USA 60) cycles (Fig. 2.9). During the time that the current is cut, no power is dissipated, so that indeed energy is saved. These systems are called phase-cutting systems. They are small enough to fit into a wall switch box or cord switch.

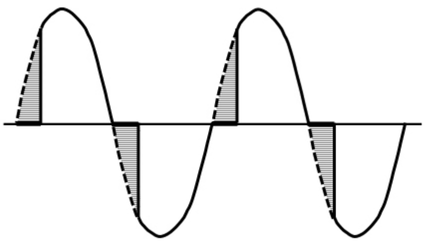


Fig. 2.9 Phase cutting of AC current.

A dimmed incandescent lamp will have a lower filament temperature, which results in a longer life and lower colour temperature (warm-coloured light). The lamp efficacy while dimming decreases, which means that the percentage of power saved is less than the percentage reduction in light output.

### 2.3.10 Mains-voltage variations

An over-voltage of even a few per cent results in a drastically-reduced lamp life. For example, a permanent overvoltage of 5 per cent reduces the lamp life by 50 per cent.

## 2.4 Product range

The product range of incandescent lamps comprises not only general lighting service lamps (in clear, frosted, opal and coloured versions) but also reflector lamps, tubular lamps, decorative lamps, beacon lamps, vehicle lamps (bicycles, cars, trains), signal lamps and studio and theatre lamps. Figure 2.10 shows some examples of these lamps. All these lamps have blown-glass bulbs (blown from a single “blob” of glass), with the exception of the pressed-glassreflector lamp (PAR, Parabolic Aluminised Reflector). The latter is moulded in two pieces, which are sealed together - they are also sometimes called sealed-beam lamps. One advantage of this construction is that the mirror in the rear and the refractor on the front can be accurately shaped to increase the beam quality and efficiency. Another advantage is its high mechanical and thermal strength, allowing the lamp to be used outdoors without a protecting luminaire.


Fig. 2.10 Examples of different incandescent lamp types.

# 3 Halogen lamps

During the operation of incandescent lamps, tungsten evaporates from the filament and settles on the coldest place inside the lamp (the bulb wall), causing lamp blackening, which leads to a considerable depreciation of the light output during lamp life. In order to keep lamp blackening, and the corresponding light loss, within acceptable limits, bulbs of normal GLS lamps are relatively large. But in order to be able to operate small-bulb high-light-output incandescent lamps, special measures have to be taken to prevent bulb blackening, which in these small bulbs would quickly lead to unacceptable light losses. The solution to this problem is to introduce halogen into the bulbs. These lamps are called halogen-incandescent or, in short, halogen lamps. Thanks to their compactness they are extremely suitable for use in small reflectors to create well-defined light beams. They are widely used for accent lighting and in car headlamps. However, because of the relatively low efficacy and short lifetime of halogen lamps, the more efficient and longer-life gas discharge and solid-state lamp alternatives have become increasingly more important in all these segments.

## 3.1 Working principle

### 3.1.1 Halogen cycle

One way to eliminate bulb blackening is to add a small quantity of halogen (bromide or iodine) to the fill gas. Under the influence of the hot filament, evaporated tungsten particles chemically combine with the halogen particles. If the temperature is sufficiently high (bulb temperature at least 250°C), the resulting mixture will remain floating in a gaseous state, so preventing it from condensing on the coldest part of the lamp bulb to create bulb blackening. The extremely-high temperature in the vicinity of the filament causes a chemical reaction that splits the mixture into its original components, tungsten and halogen particles, and the former return to the filament. This phenomenon is called the halogen cycle. It is illustrated in Fig. 3.1.

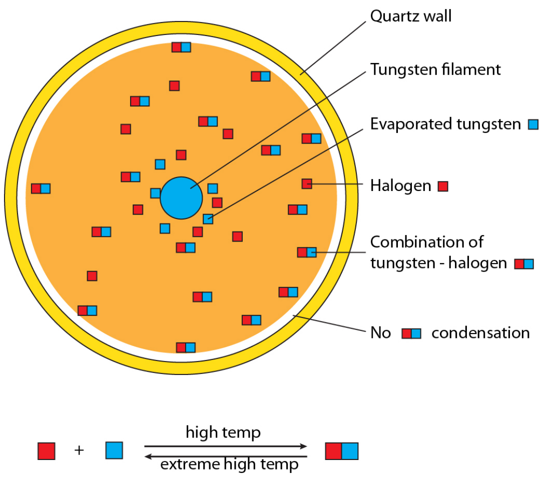



Fig. 3.1 The halogen cycle.

A tungsten particle that escapes from one spot of the filament does not return to exactly the same spot. As a result, the lamp will eventually burn out, because there will always be some part of the filament that will become weak over the course of time, but clearly later than in a normal incandescent lamp. This means that the filament can be heated up to a higher temperature (up to 3000 K instead of 2750 K in the case of a normal incandescent lamp) while having a longer life. Halogen lamps offer two to five times the life of normal incandescent lamps, rising from 1000 hours to 2000 to 5000 hours. The higher filament temperature also increases both the luminous efficacy by 10 to 50 per cent relative to normal incandescent lamps and the colour temperature up to 3000 K.

### 3.1.2 Cool-beam technology

A special version of halogen lamps, the so-called cool-beam lamps, make use of the interference principle explained in Section 3.5 of the book "Basics of Light and Lighting". They consist of a small halogen bulb (capsule) housed in a reflector with an interference metal coating, also known as a ¼ λ, or dichroic coating (Fig. 3.2). This coating splits the radiation coming out of the halogen capsule into an infrared part (heat), which is transmitted through the coating and not reflected by it, and a visible part that is reflected but not transmitted. The practical result is that the mirror coating reflects practically all of the light (95 per cent) while allowing the infrared to pass through it to the back of the reflector, taking about 2/3 of the heat from the light beam. Thus only 1/3 of the generated heat is contained in the light beam. This is why these lamps are referred to as "cool-beam", or "dichroic" halogen lamps. When using this type of lamp in an installation it is important to ensure that the heat radiated from the rear of the lamp can be dissipated backwards.

As explained in the book Theory of light and lighting (Section 3.5) interference is based on the thickness of the coating (¼ λ thickness). The thickness of the coating layer is slightly different for radiation arriving at the coating from different directions. This also means that the wavelength of the radiation where it is split into reflected and transmitted components is slightly different for different directions. This is why cool-beam lamps always show slightly reddish colour effects when looking at the reflector. Reddish effects, because red is on the border between visible and infrared radiation. Compare this with the bright colours on a soap bubble, which are also caused by interference.

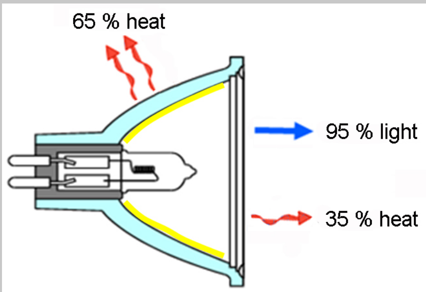



Fig. 3.2 Effect of the dichroic interference coating (shown in yellow) in a cool-beam halogen lamp.

### 3.1.3 Infrared reflective-coating technology

Another special version of the halogen lamp, called the IRC halogen lamp, also makes use of the interference coating principle, but for a completely different reason. Here the reason is thermal recovery: the interference coating applied to the halogen bulb is now so dimensioned that it reflects the infrared radiated from the filament back to the filament while allowing visible light to pass through (Fig. 3.3). In this way less external energy is needed to keep the filament at the required temperature, thus improving the efficacy of the lamp (by up to 25 lm/W to 35 lm/W). Moreover, the heat contained in the light beam is reduced by approximately 40 per cent, resulting in a more comfortable environment and a lower air-conditioning load.

This lamp type is called, after its technology, the Infrared Reflective Coating, or IRC, halogen lamp. After its energy-saving effect, it is also known as the Energy Saving, or ES, halogen lamp.

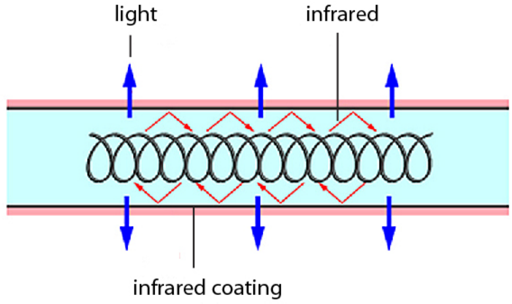



Fig. 3.3 Infrared reflective coating based on the interference principle used to reflect the infrared radiation of the filament back to the filament while allowing visible light to pass through.

## 3.2 Lamp construction

### 3.2.1 Bulb

Since a halogen bulb is so small (Fig. 3.4) it becomes so hot that normal glass, as used with incandescent lamps, cannot be used because it would melt. Halogen bulbs are therefore made out of quartz, which can withstand high temperatures and mechanical stress. In the manufacturing process it can be handled similarly to glass.

### 3.2.2 Filament

The single or double-coiled tungsten filament can be placed axially or transversely in the halogen capsule (Fig. 3.4). The placement has consequences for both the efficacy and the light distribution of the lamp.

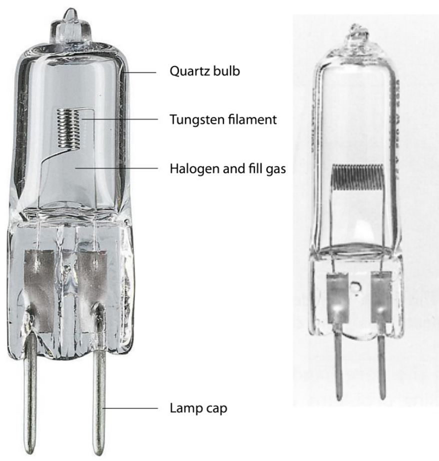



Fig. 3.4 Halogen lamp with its components. The bulb can be as small as approximately 10 x 15 mm. Left: axial filament. Right: transverse filament.

### 3.2.3 Fill gas

As in normal incandescent lamps, a gas filling of krypton or xenon is used to reduce filament evaporation.

### 3.2.4 Lamp cap

Halogen lamps are available with a large variety of lamp caps and corresponding bases. Fig. 3.5 gives some typical examples: two-pin caps and twist caps that ensure that the optical centre of the lamp is always in the correct position, ceramic lamp caps for high-voltage, high-lumen-output lamps that become very hot, and "normal" Edison and bayonet caps for high-voltage halogen lamps that can be used just as normal incandescent lamps.

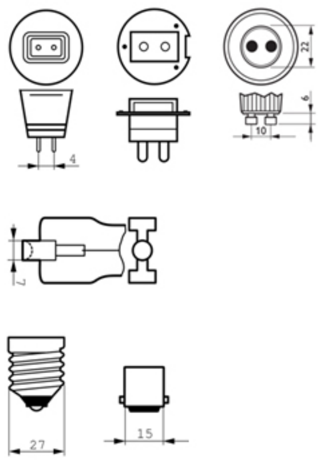



Fig. 3.5 Typical examples of different halogen lamp caps.

## 3.3 Performance characteristics

### 3.3.1 Energy balance

Thanks to the higher working temperature of the halogen incandescent lamp, it is more efficient than a normal incandescent lamp. Some 12 per cent of the input power of a halogen lamp is radiated as visible light. Compare this with the 8 per cent of a normal incandescent lamp. The remaining power is lost as heat (through conduction, convection and infrared radiation).

### 3.3.2 Luminous efficacy

At 15 lm/W to 25 lm/W, the luminous efficacy of a halogen lamp is a factor 2 to 2,5 higher than that of an incandescent lamp. With the infrared-reflecting coating, or IRC technology, the efficacy increases to some 35 lm/W. As with normal incandescent lamps, the lower the wattage, the lower the efficacy. There are halogen lamps where priority has been given to a long life at the expense of a somewhat lower efficacy (e.g. 5000 h and 15 lm/W) and, conversely, there are those where the emphasis is on efficacy and not so much on lifetime (e.g. 2000 h and 25 lm/W).

Although the efficacy of halogen lamps is clearly higher than that of normal incandescent lamps, it is relatively low compared with that of gas discharge and solid-state light lamps.

### 3.3.3 Lumen-package range

Common types of halogen lamps are available in the range from some 50 to 2000 lumen (corresponding wattage range approximately 5 W to 100 W). So-called double-ended mains-voltage halogen lamps are available in versions up to some 25 000 lumen (1000 W version).

### 3.3.4 Colour characteristics

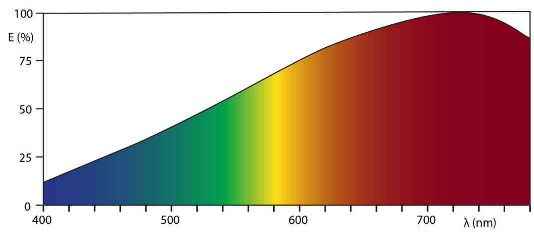



Fig. 3.6 Relative spectral energy distribution of a halogen lamp.

Halogen lamps have a continuous spectrum radiating more energy at long wavelengths than at short wavelengths (Fig. 3.6). Because of the somewhat higher temperature of the filament in halogen lamps compared to that of the filament in normal incandescent lamps, the spectral energy distribution shifts slightly towards shorter wavelengths. Depending on the version (lower efficacy / longer life or higher efficacy/ shorter life), halogen lamps have a colour temperature of between 2800 K and 3000 K, respectively. Their colour temperature is always slightly higher than that of normal incandescent lamps, thus giving them a somewhat cooler white light. The colour rendering index is 100.

### 3.3.5 Lamp life

Normal halogen lamps have a lifetime that is at least twice as long as that of normal incandescent lamps – thus at least 2000 h. As explained above, with some halogen lamps priority is given to efficacy at the expense of lifetime: viz. the 2000 h versions. Versions where the priority is given to lifetime can have a life of up to 5000 h.

### 3.3.6 Lamp price

Depending on type, halogen lamps are just a little bit more expensive than normal incandescent lamps, and roughly five times more expensive for some reflector types. High-voltage PAR versions may be up to fifteen times more expensive than an ordinary GLS lamp.

### 3.3.7 Lamp-lumen depreciation

Thanks to the halogen regenerative cycle, lamp blackening is minimal. Consequently, lumen depreciation with halogen lamps is very small.

### 3.3.8 Burning position

With certain exceptions, halogen lamps have a universal burning position. The exceptions are the high-voltage, high-wattage (750 W or more) double-ended types. Here the coiled tungsten filament is so long that with a position that is not near horizontal, the coil would sag so much that the individual coil windings would touch each other, leading to a short circuit.

### 3.3.9 Run-up and re-ignition

Like normal incandescent lamps, halogen lamps give their full light output immediately after switch-on and after re-ignition.

### 3.3.10 Switching

The switching behaviour of halogen lamps is the same as that of normal incandescent lamps (see Section 2.3.8).

### 3.3.11 Dimming

Halogen lamps can be dimmed in the same way as normal incandescent lamps (see Section 2.3.9). Just as with normal incandescent lamps, the phase-cutting system is the more efficient system, and is that usually employed. Below a certain dimming point the lamps cool down so much that the halogen cycle will no longer function. From this point on the filament starts evaporating, just as with a normal, dimmed incandescent lamp. The smaller bulb size of the halogen lamp leads to more blackening in this situation than is the case with normal incandescent lamps. However, since the filament in the dimmed situation is cooler than in the undimmed situation, dimming does not have a real negative effect on the lamp life.

### 3.3.12 Mains-voltage variations

The behaviour of halogen lamps as a result of an overvoltage is the same as with normal incandescent lamps. Only a few per cent of overvoltage results in a drastically-reduced lamp life. For example, a permanent overvoltage of 5 per cent reduces the lamp life by 50 per cent.

### 3.3.13 UV component

Normal incandescent lamps radiate little UV. This is because the spectrum quickly falls off at the short-wavelength part of the spectrum (Fig. 3.6). What little UV that remains is reduced to near zero because normal glass (the bulb material of incandescent lamps) is a very good absorber of UV radiation. Halogen lamps radiate more UV because of the higher operating temperature of the filament, and because of the fact that normal quartz bulbs, unlike glass bulbs, do not absorb UV radiation. In order to limit harmful or damaging UV radiation from halogen lamps, the quartz used today for most halogen lamps is doped with UV-absorbing material (UV-block quartz glass).

## 3.4 Product range

As far as operating voltage is concerned, halogen lamps can be placed into two groups (Fig. 3.7).

- lamps operating on low voltage (6 V, 12 V and 24 V, where the 12 V versions are most common);
- lamps operating on mains voltage.

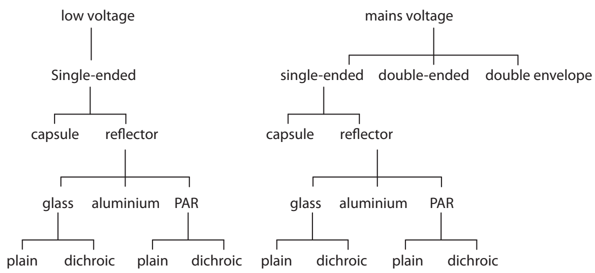



Fig. 3.7 Range of halogen lamps.

Low-voltage halogen lamps are usually single-ended. Mains-voltage versions can be either single-ended or double-ended, according to whether the electrical connection is at one end of the lamp (single) or on two separated ends of the lamp (double), as illustrated in Figs 3.8 and 3. 9 respectively.

Fig. 3.8 Single-ended halogen capsule (low voltage) and single-ended halogen reflectors lamps (left: low voltage right: mains voltage).

Fig. 3.9 Double-ended mains-voltage halogen lamp.

Single-ended halogen lamps are available both as "naked" bulbs (capsules) and as reflector lamps (see again Fig. 3.8). The reflector versions exist in three different types: mirror-coated glass reflectors (Fig. 3.10), and aluminium reflectors and pressed-glass PAR reflectors (Fig. 3.11). The mirror-coated glass reflectors are produced with plain mirror-coating versions and with a dichroic coating (viz. cool-beam type).

Fig. 3.10 Mirror-coated glass halogen reflector lamps. Left: dichroic coating (cool-beam type), right: plain mirror coating.

Fig. 3.11 Aluminium (left) and pressed-glass (right) PAR halogen reflectors.

Some mains-voltage halogen bulbs (both single-ended and double-ended) are housed in an extra outer glass bulb or glass tube with the familiar Edison or bayonet lamp cap. These are called double-envelope halogen lamps (Fig. 3.12). They are the more-energy-efficient replacements for normal incandescent lamps.

Where halogen lamps without outer bulb should not be handled with bare fingers, lamps with an outer bulb or tube can be handled normally. [3]

Fig. 3.12 Double-envelope mains-voltage halogen lamps.

3 The fat of fingers left on a bare halogen capsule is baked onto the very hot capsule when the lamp is switched on next time and this shortens its lifetime.

# 4 Tubular fluorescent lamps

Fluorescent lamps belong to the family of low-pressure mercury gas discharge lamps. They are by far the most widespread discharge lamp types. They are available in both tubular and compact versions. Although the operating principle of compact fluorescent lamps is largely the same as that of the tubular version, their construction and performance is in many ways different from that of the tubular version. The compact fluorescent lamp will therefore be dealt with in a separate chapter (Chapter 5).

The Philips designation for tubular fluorescent lamps is 'TL'. Tubular fluorescent lamps are widely used in offices, schools and low-ceilinged industrial premises.

## 4.1 Working principle

Tubular (and compact) fluorescent lamps are gas discharge lamps. The use of gas discharge lamps is explained in Section 2.2 of the book "Theory of Light and Lighting".

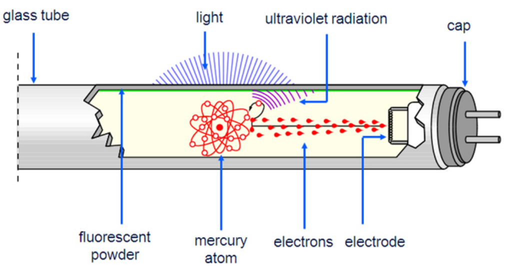



Fig. 4.1 Main parts and principle of operation of a tubular-fluorescent gas discharge lamp (TL).

The discharge tube of a tubular fluorescent lamp is filled with an inert gas and a little mercury and has an electrode sealed into each end (Fig. 4.1). To facilitate starting, the electrodes of most fluorescent lamps are pre-heated prior to ignition, which is accomplished by means of a high-voltage pulse, generated by an external device called the 'igniter' (dealt with in more detail in Chapter 13). When the lamp is switched on, the electrodes begin emitting electrons, and through collision of these electrons with the gas atoms the ionisation process starts. The inert gas is then heated up and the mercury inside the lamp is completely evaporated to give a mercury vapour pressure of about 0.8 Pa (8.10-6 atm). The emitted electrons collide with and excite the mercury atoms, resulting in the emission of ultraviolet radiation and a small amount of blue visible light. The inside of the discharge tube is coated with a mixture of fluorescent powders. The ultraviolet radiation is converted to visible light when it passes through the fluorescent powder coating.

Like almost-all gas discharge lamps, a fluorescent lamp cannot be operated without some device to limit the current flowing through it. This device is called a 'ballast', which will be dealt with in the Section allocated to control gear (Chapter 13).

## 4.2 Lamp construction

The main parts of a tubular fluorescent lamp are (see Fig. 4.1):

- glass tube
- fill gas
- electrodes
- fluorescent powder
- lamp caps

### 4.2.1 Glass tube

The tube of a normal fluorescent lamp is made of glass that is doped with a special material that blocks that UV radiation from the mercury discharge that is not converted by the fluorescent powder into visible light. [4]

The original fluorescent lamp had a diameter of 38 mm, for which the Philips designation is TL. This tube diameter is usually characterized as T12, where the 12 stands for 12 times 1/8 of an inch (Fig. 4.2 and Table 4.1). This type of fluorescent tube is seldom seen today. During the late-eighties of the last century a smaller and more efficient version was introduced that has a diameter of 26 mm – Philips designation TL-D.[5] Today an even thinner and more efficient version has become the standard: the TL5 with a diameter of 16 mm. Even thinner fluorescent lamps are produced, but these are not for use in general lighting.

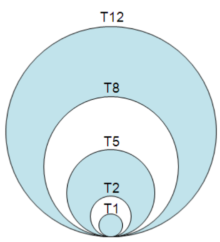



Fig. 4.2 Different fluorescent tube diameters.

4 Sun-tan lamps employ a different kind of glass to allow the UV radiation to pass through.

5 The "D" here stands for the Dutch word "Dun" meaning "thin")

| Philips designation | Tube type | Modular size | Diameter |
|---|---|---|---|
| TL | T12 | 12 * 1/8 inch | 38 mm |
| TL-D | T8 | 8 * 1/8 inch | 26 mm |
| TL5 | T5 | 5 * 1/8 inch | 16 mm |
| T2 | T2 | 2 * 1/8 inch | 6 mm |
| T1 | T1 | 1 * 1/8 inch | 2.8 mm (T1.5: 4.6) |

Table 4.1 Fluorescent lamps with different tube diameters and their designations.

### 4.2.2 Fill gas

The gas filling in a fluorescent lamp consists of a mixture of mercury vapour and an inert gas. The inert gas has three functions :

- to facilitate ignition, especially at lower temperatures
- to control the speed of the free electrons
- to prolong the life of the electrodes by reducing evaporation of electrode material

The inert gas usually consists of a mixture of argon and neon, although sometimes krypton is used as well.

For environmental reasons it is, of course, essential that the minimum dose of mercury required be used and that spillage during production of the lamps is completely avoided. During operation of the lamp, some of the mercury is absorbed by lamp components (such as the glass tube, fluorescent powder and electrodes) and so does no longer contribute to the gas discharge process. The mercury dose must therefore be based on the expected mercury consumption during the lifetime of the lamp. Advanced dosing systems ensure that the exact amount of mercury required is safely introduced into the lamp.

The exact amount of mercury needed for the discharge tube is not brought directly into the gas discharge tube but is very-accurately dosed into a small glass or metal capsule, which is mounted in the discharge tube (shown in Fig. 4.4). At the end of the production process, the mercury is released into the gas discharge tube itself by heating the capsule so that it breaks open (Philips patent).

### 4.2.3 Electrodes

The function of the electrodes is to provide free-running electrons, which are necessary to start and maintain the discharge. A fluorescent lamp electrode consists basically of a tungsten filament (Fig. 4.3) that is coated with so-called emitter material to facilitate electron emission. In most fluorescent lamps the electrodes are preheated to about 800°C by an igniter that supplies a preheating voltage.

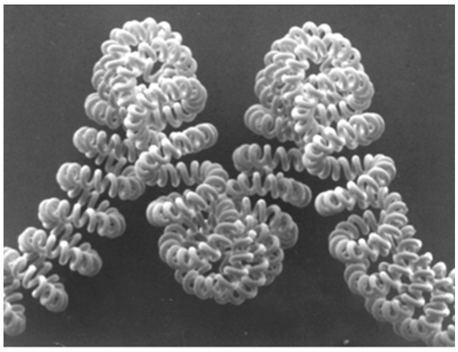


Fig. 4.3 Triple-coiled filament electrode.

During its life, the electrode loses emitter material due to both evaporation and scattering as a result of the bombardment from the discharge. In most fluorescent lamps the electrode filament is surrounded by a flat metal ring (Fig. 4.4) that prevents scattered emitter material from being deposited on the nearby tube wall, which would cause blackening and consequently lumen depreciation (Fig. 4.5).

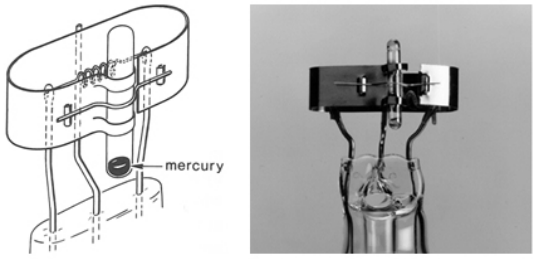



Fig. 4.4 Metal ring surrounding the electrode filament with mercury capsule connected to it.

Fig. 4.5 Blackening of fluorescent tubes because of scattering of emitter material from the electrodes (no protecting ring).

### 4.2.4 Fluorescent powder

The small crystals of the fluorescent powder applied to the inside of the discharge tube absorb the UV mercury radiation and convert it into visible light (this physical phenomenon is called luminescence). Different fluorescent powders convert the ultraviolet radiation into visible light of different wavelengths and thus different colours (Fig. 4.6).

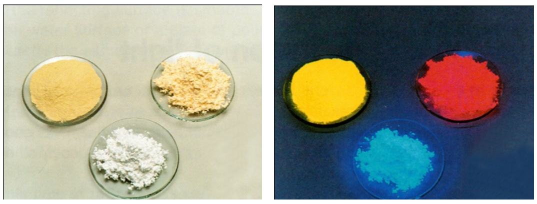


Fig. 4.6 Left: three different types of fluorescent powder under white light. Right: The same fluorescent powders under UV radiation.

Fluorescent powders are very much a product of modern chemical technology. A large number of fluorescent powder compounds have been discovered. Fluorescent compounds contain rare earth metals.[6] By mixing different fluorescent powders in different proportions, lamps producing different tints of white light can be made. The type and composition of the fluorescent powder is the most important factor determining the light characteristics of a fluorescent lamp, such as colour temperature, colour rendering index (Ra), and to a large extent the luminous efficacy of the lamp (lm/W).

Some fluorescent powders convert the ultraviolet radiation into wavelengths covering almost the whole visible spectrum. Such powders therefore produce white light when used alone. However, their colour rendering and efficacy is poor (Ra < 70 and lm/W < 80 - Fig. 4.7 top). Because these powders lose some of their conversion activity relatively quickly, lamp-lumen depreciation is relatively large (more than 30 per cent at the end of life). Nowadays these lamps are hardly ever produced. Today fluorescent lamps often employ a mixture of three fluorescent powders, each having a very narrow spectrum band in red, green and blue. In this way white light is again obtained, but of better colour rendering and efficacy (Ra > 80, lm/W up to 105 - Fig. 4.7 middle). The lamp-lumen depreciation with these powders is very low (< 10 per cent). For cases where extremely good colour rendering is required, a mixture of more than three powders is used, resulting in lamps with excellent colour rendering (Ra >90), very low lumen depreciation, and high luminous efficacy (slightly smaller than the previous version, viz. up to some 90 lm/W - Fig. 4.7 bottom).

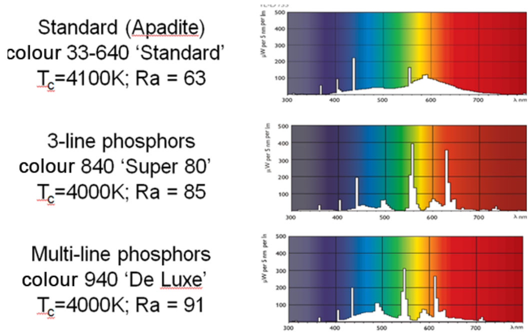



Fig. 4.7 Spectral energy distributions of different types of fluorescent lamp using different compositions of fluorescent powders.

### 4.2.5 Lamp cap

Some examples of lamp caps for fluorescent lamps are shown in Fig. 4.8. A lamp with pre-heated electrodes needs caps that each have two contacts for the pre-heating of the electrode filaments. So-called cold-start lamps need only single-contact caps. Circular lamps have a single cap with four-contacts, two for each electrode, again for pre-heating them. Heavily-loaded lamps have recessed contacts for safety reasons, and lamps for use in explosion-risk areas have their own "safety" cap.

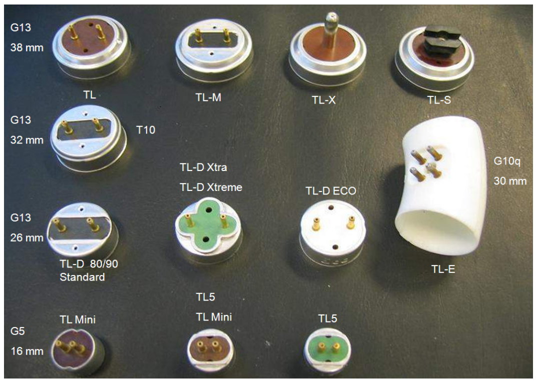



Fig. 4.8 Variety of different lamp caps employed with tubular fluorescent lamps.

Lamp caps and their designation are standardised by the IEC (International Electrotechnical Commission).

Caps with green bottom plates are for those lamps that are completely recyclable; brown is for the normal version; while white is for the ECO version (aimed at reducing the environmental impact according to EU regulations).

6 Rare earth metals belong to a group of 17 metal elements with very specific properties also widely used in energy technology devices.

## 4.3 Performance characteristics

### 4.3.1 Energy balance

Fig. 4.9 shows the energy balance of a typical fluorescent tube. It shows that just under 30 per cent of the input power is converted into visible radiation and a very small part into UV radiation. The rest is lost in the form of heat (at the electrodes, in the discharge itself and as infrared radiation). The energy losses in the ballast are not shown.

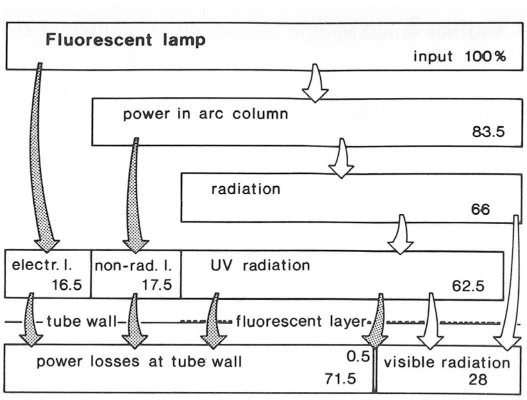



Fig. 4.9 Energy balance of a typical fluorescent tube (electr. L. = electrodes losses; non-rad. L. = non-radiation losses).

### 4.3.2 System luminous efficacy

As with most lamps, the luminous efficacy of tubular fluorescent lamps is dependent on the wattage of the lamp and the colour quality of the light it gives. Types with colour rendering better than $R_a$ 80 and with low lumen packages have a system luminous efficacy starting at 50 lm/W, while lamps with higher lumen packages reach efficacies up to some 105 lm/W. Lamps with extremely-good colour rendering ($R_a$ > 90) have 15 per cent lower efficacies.

### 4.3.3 Lumen-package range

Common tubular fluorescent lamps are produced in the range from some 500 lm to 6000 lm (corresponding wattage range approximately 8 W to 80 W). Special very-high output lamps are also produced in versions up to some 9000 lm (120 W).

### 4.3.4 Colour characteristics

As has been shown in the Section 4.2.4 ("Fluorescent powder"), by mixing different fluorescent powders in different proportions, lamps with different spectra can be produced. As with all gas discharge lamps, the spectrum is discontinuous. Figs 4.10 to 4.12 show the spectra of fluorescent tubes with different colour temperatures CCT and colour rendering index $R_a$.

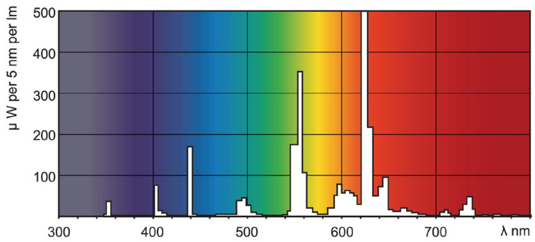



Fig. 4.10 Spectral energy distribution of a fluorescent lamp colour type 827: $T_k$ 2700 K and Ra 80.

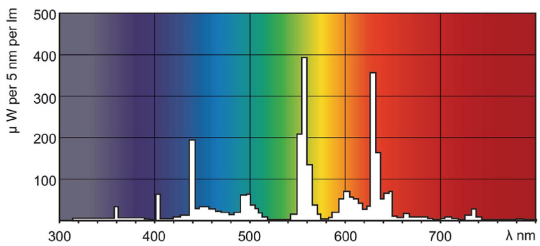



Fig. 4.11 Spectral energy distribution of a fluorescent lamp colour type: 840: $T_k$ 4000 K and Ra 80.

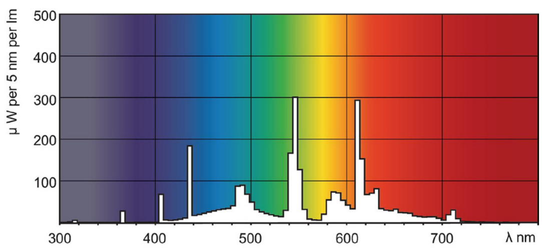



Fig. 4.12 Spectral energy distribution of a fluorescent lamp colour type 940: 840: $T_k$ 4000 K and Ra 90.

The colour type designation used for fluorescent lamps is standardised, with the first digit standing for the colour rendering index $R_a$ and the last two digits for the colour temperature CCT. Thus the colour type 840 stands for a colour rendering index value $R_a$ in the 80-ties and a colour temperature of around 4000 K.

Present-day quality fluorescent lamps are produced in a whole range of colour temperatures varying from 2700 K (warm-white or incandescent lamp colour tint) to 6000 K (bluish-white), most of them in two colour-rendering qualities with Ra in the 80s (800 series) and 90s (900 series) respectively. For special applications, versions are produced with extremely-high colour temperatures (up to some 17 000 K) with colour rendering in the 80s. Today, we find fewer and fewer of those fluorescent lamps with poor colour rendering qualities (viz. Ra around 65 or less) that were produced in the past.

### 4.3.5 Lamp life

During the operation of a lamp, the electrodes lose emitter material due to evaporation and as a result of the bombardment with ions from the discharge. This is the main cause of final lamp failure: the lamp will no longer start, due to a broken electrode, or else it flickers because insufficient emitter material remains. The lifetime of fluorescent lamps and gas discharge lamps in general is thus very much dependent on the construction and materials of the electrodes. Lamp manufacturers can supply life-expectancy curves for their various lamp types measured under defined IEC conditions (see example, in Section 1.2.5, Fig 1.3). Conditions that influence lifetime are principally the type of gear used, the switching frequency and the ambient temperature. The switching frequency plays a role because the high voltage peak needed for ignition causes the electrodes to lose some of their material (sputtering). The more accurately the igniter-ballast combination pre-heats the electrodes (see Chapter 13), the less severe this effect is. The occurrence of such things as shocks or vibrations, different burning positions and supply-power variations can play an additional role.

Today's high-quality fluorescent tubes have economic lifetimes (based on 20 per cent mortality) of 15 000 h to more than 20 000 h if used on a so-called high-frequency or HF ballast, and around 12 000 h when used on an electromagnetic ballast. For situations where the actions needed to replace lamps are expensive, special, more expensive, long-life fluorescent lamp versions are available with lifetimes ranging from some 40 000 h to 65 000 h (Philips types "Xtra" and "Xtrema"). This long life is obtained by means of a special electrode design and construction.

### 4.3.6 Lamp price

Normal fluorescent tubes are some two to five times more expensive than GLS lamps. Special types, such as extremely-long-life lamps may be up to ten to fifteen times more expensive than GLS lamps.

### 4.3.7 Lamp-lumen depreciation

The main cause of lamp-lumen depreciation in a fluorescent lamp is that the fluorescent powder slowly becomes less active as a result of chemical attack by mercury ions. There may also be some blackening of the tube wall from the electrodes. For cool-white and cool-daylight lamp types, the lumen depreciation is higher than for lamps with a warmer tint. This is because of the faster depreciation of the blue fluorescent powders. Lamp manufacturers can supply lamp-lumen depreciation curves for their various lamp types (see example in Section 1.2.6, Fig 1.4). These curves show that lamp-lumen depreciation for present-day high-quality fluorescent tubes is approximately10 per cent after some 20 000 hours.

### 4.3.8 Run-up and re-ignition

Fluorescent lamps operated on present-day electronic control gear start very quickly (within one and a half seconds) and without flickering. This is in contrast to lamps used on the older, glow-switch starters. After ignition, the light output increases quickly up to its maximum in about one minute. Special "extreme-temperature lamps" (see Section 4.3.11) have a run-up time of about three minutes.

When a fluorescent lamp is switched off, the vapour pressure drops so quickly that re-ignition is instantaneous.

### 4.3.9 Switching

In the Section "Lamp life" it has already been mentioned that the switching frequency has an influence on lifetime, the influence being dependent on the type of electrical control gear used. Lamps operated with HF electronic-preheat-start ballasts (see Section 13) show, in general, little sensitivity to the switching cycle. This is because of the well-controlled starting conditions of the lamp (warm start). HF non-preheat starting leads to a relatively short lamp life under frequent-switching conditions. For this reason, coldignition is not recommended with frequent switching. However, cold ignition can be an economical option for infrequently-switched lamps (e.g. lamps burning for at least 8 hours per switch).

IEC standards specify for laboratory lifetime measurements a three-hour switching cycle (2 h 45 min. on and 15 min. off). This so-called IEC switching cycle implies eight switching cycles per 24 hours. However, in practice, switching frequencies are usually much lower. Lifetime values based on a 12-hour cycle (e.g. 11 h 30 min. on and 30 min. off), implying two switching cycles per 24 hours, are much closer to real market practice.

### 4.3.10 Dimming

Dimming of modern fluorescent lamps on high-frequency electronic ballasts down to three per cent of the nominal light-output value is possible with an additional circuit that changes the operating frequency (see Chapter 11).

### 4.3.11 Ambient-temperature sensitivity

The luminous flux of a fluorescent lamp is determined by the mercury vapour pressure during operation. The mercury vapour pressure is in turn determined by the coldestspot in the tube, normally the tube wall, which of course is also dependent on the ambient temperature. The consequence of this is that the light output of fluorescent lamps is dependent on ambient temperature.

The location of the coldest spot can be influenced by the design of the discharge tube. In this way, the temperature dependency can be influenced to a certain extent. Figure 4.13 shows the location of the cold spot in two different versions of fluorescent tubes, TL / TL-D respectively TL5. The asymmetrical positioning of the (hot) electrodes in the TL5 version moves the cold spot from the middle of the tube wall towards one end of the tube.

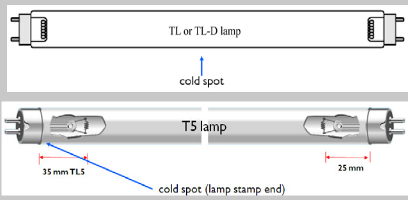



Fig. 4.13 Moving the coldest spot from the middle of the tube wall in TL and TL-D lamps towards one of the ends of the tube in TL-5 by making the electrode positions asymmetrically.

The lumen output of fluorescent lamps is generally published for an ambient temperature of 25°C. TL and TL-D lamps have their maximum light output at 25°C, while the smaller diameter TL5 lamps give their maximum light output at 35°C (see Fig. 4.14).

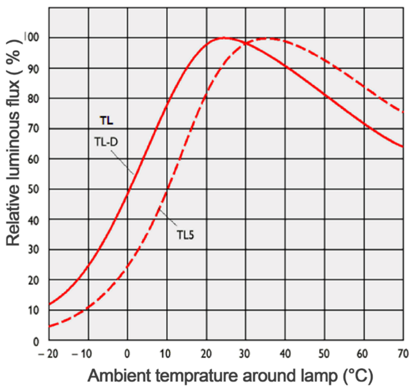



Fig. 4.14 Relative light output of a TL-D and a TL5 fluorescent lamp in relation to the lamp ambient temperature.

Many TL5 luminaires are designed so that the ambient temperature in the luminaire is around 35°C. This is why the lumen output for TL 5 lamps is usually published at both 25°C (IEC prescription) and at 35°C, which is the sometimes more realistic value in practice.

To obtain a high and near-constant light output over a wide temperature range, the mercury in some fluorescent lamp types is introduced into the tube not as a pure metal but as an amalgam. An amalgam is a chemical compound of mercury and other metals (also sometimes used by the dentist as a filling material). Such lamps have a lumen output that is near constant over the temperature range of 25°C to 65°C (Fig. 4.15). [7]

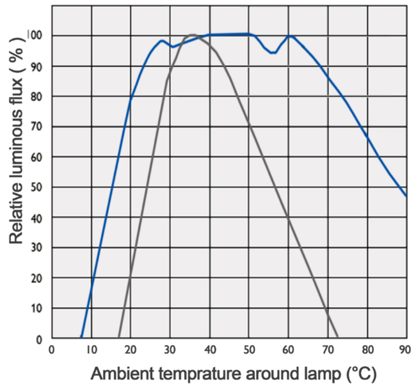



Fig. 4.15 Relative light output of a normal fluorescent lamp (grey curve) and of a T5 extreme-temperature lamp (blue curve) in relation to the lamp ambient temperature.

### 4.3.12 Mains-voltage variations

If the mains voltage varies, the power consumed by the lamp changes and with it the vapour pressure and consequently the lumen output. Given an optimised lamp/electromagnetic ballast combination, a 10 per cent deviation in power will keep the lumen-output decrease usually at less than 10 per cent. On high-quality high-frequency electronic ballasts (see Section 13) a 10 per cent deviation in power can keep the lumen-output decrease at less than 3 per cent. In all cases, with greater decreases than 10 per cent the lumen output decreases rapidly.

## 4.4 Product range

Tubular fluorescent lamps are being produced in a wide variety of types with different properties. The more important lamp characteristics, together with the range for which different versions are made, are listed in Table 4.2.

7 In an amalgam lamp, the mercury vapour pressure is determined by the amalgam itself and not by the coldest spot in the lamp.

| Lamp aspect | Range |
|---|---|
| Tube diameter | 38mm (TL) / 26mm (TL-D) / 16mm (TL5) |
| Lamp Circuit | electromagnetic (“conventional”)/HF electronic |
| Balance efficacy / lumen output | high efficacy (HE) / high output (HO) / very high output (VO) |
| Colour Temprature Tk | standard range (2700K - 6000K)/ 8000K-17000K |
| Colour rendering Ra | Ra>90 (900 series) / 80<Ra<90 (800 series)/Ra<80 |
| Colour | red; green; blue / etc. |
| Lifetime | standard (up to 20 000h.) / very long (up to 65000h. |
| Ignition method | standard / low-temperature ignition |
| Tube coating | no coating/coating (silicon)/protective/reflector |
| Safety of operation | Standard / explosion safe |
| Tube length | standard (450mm - 1800mm)/mini(150mm-500mm) |
| Tube shape | tubular/circular |

Table 4.2 Lamp characteristics with range of different lamp types.

Up until 1990, fluorescent tubes were operated on electromagnetic ballasts. Even today, this way of operating a fluorescent tube is called “conventional”, although operation on high-frequency, HF electronic ballasts has since become the standard. TL5 lamps can only be operated on HF electronic gear. More details about ballasts and gear is given in Chapter 13.

TL5 lamps are produced in a type where the design is such that the maximum luminous efficacy is obtained: the HE series of lamps. Another type is optimised for maximum lumen output at the cost of efficacy: the HO series (10 per cent higher lumen output and 10 per cent lower efficacy). Very-high-output lamps (VHO) are produced as well. These lamps, which are specifically meant for use in large industrial halls, also provide a constant lumen output over a wide range of ambient temperature (as discussed in Section 4.3.11).

Some tubular fluorescent lamps are given a coating on the outside of the tube. A silicone water-repellent coating is applied to prevent starting problems for types that are used under conditions of high humidity. Those types intended for use in food stores can be given a special protective coating that prevents surrounding products from contamination in the event of accidental lamp breakage. Some of these latter types have a spectrum that makes the appearance of food more appealing (especially meat). In reflector fluorescent lamps, a diffuse reflective coating is applied between the upper part of the inner tube wall and the fluorescent powder. The light is concentrated through the uncoated area (or “window”) of the lamp, so increasing the downward component of the light (Fig. 4.16).

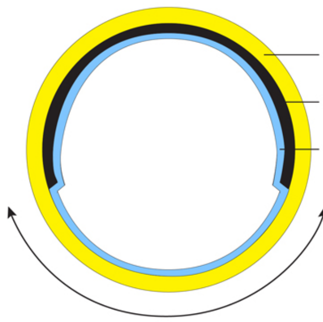



Fig. 4.16 Reflector fluorescent lamp, showing the reflective coating (in black) on the upper part.

# 5 Compact fluorescent lamps

Compact fluorescent lamps (CFLs) were originally developed (beginning of the 1980's) for use in those applications where incandescent lamps were traditionally used. Today, the application of compact fluorescent lamps has been widened and includes not only domestic lighting but office and road lighting (residential streets) as well. For the more compact versions, alternatives in the form of solid-state lamps are becoming increasingly more available.

The Philips designation for many compact fluorescent lamp types is "PL".

## 5.1 Working principle

The gas discharge principle employed in compact fluorescent lamps is exactly the same as that in tubular gas discharge lamps (see Section 4.1). Their compactness is achieved by reducing their length. This is done either by folding a longer tube into a shorter one, or by joining together two or more parallel tubes so that one open pathway is obtained where free electrons and ions can move from one electrode to the other, as in a normal straight fluorescent tube (Fig. 5.1).

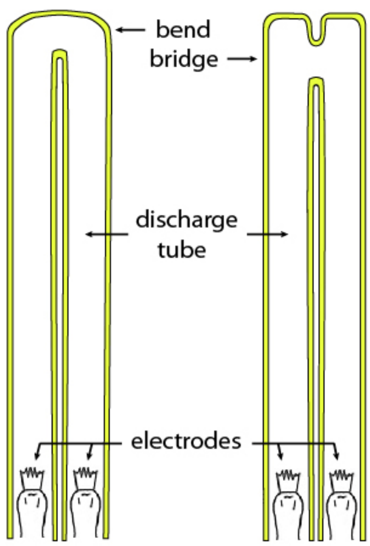



Fig. 5.1 Folding one tube (left) or connecting two separate tubes (right) to form a compact fluorescent lamp with one open pathway between the electrodes.

The folding can be repeated or the interconnection can be done with more than two parallel tubes (always keeping one open pathway) to further increase the size of the lamp.

## 5.2 Lamp construction

As far as fill gas, electrodes and fluorescent powders are concerned, compact fluorescent lamps are essentially the same as conventional tubular fluorescent lamps. Reference is therefore made to the corresponding sub-sections in Section 4.2.

The main difference in construction between compact and tubular fluorescent lamps lies in the tube shape and the lamp caps. But another point of difference is that in those compact lamps that need to work directly from the mains without any external electrical component, the igniter and ballast have to be integrated in the lamp itself. In this case the lamp base is used for housing the control gear.

### 5.2.1 Tube

A great variety of tube shapes are produced. Fig 5.2 shows versions where tubes are interconnected. Fig. 5.3 shows a set of triple-folded types, while Fig. 5.4 shows a folded, single-plane version. All these are examples of compact fluorescent lamps where the gear is not integrated in the lamp itself (compact fluorescent lamps non-integrated CFL-NI).

Fig. 5.2 Compact tubular fluorescent lamps. Each of the four lamps on the left comprises two interconnected tubes (PL-S and PL-L lamps) while each of the two lamps on the right comprises four interconnected tubes (PL-C lamps).

Fig. 5.3 Triple-folded tubes (PL-T lamps).

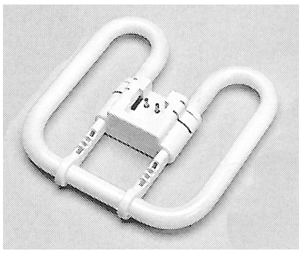


Fig. 5.4 Single-plane folded lamp (PL-Q).

Fig. 5.5 shows examples of compact lamps where the gear (HF electronic) is integrated in the lamp foot (integrated CFL-I). Since these lamps can directly replace incandescent lamps, it is also desirable that their shape and dimensions should be very close to those of normal incandescent lamps. Fig. 5.6 shows such a retro-fit version where an outer bulb with an internal diffusing coating also ensures that the light distribution is close to that of an incandescent lamp.

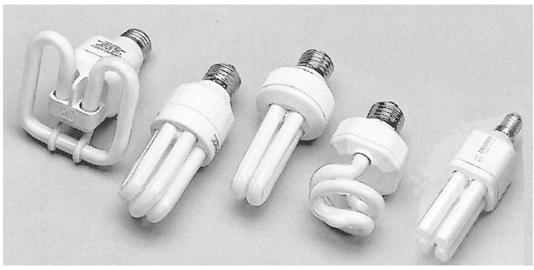


Fig. 5.5 Differently-shaped integrated compact fluorescent lamps.

Fig. 5.6 Retro-fit compact fluorescent lamp with shape, dimensions and light distribution close to that of a GLS bulb.

### 5.2.2 Lamp cap

The compact fluorescent lamps with integrated control gear have the same lamp caps as normal incandescent lamps, viz. Edison screw type and bayonet caps.

In most non-integrated, small, twin-tube versions (PL-S) the starter is built into the lamp cap itself (integrated starter but non-integrated ballast). All non-integrated types are fitted with special caps. A large variety of caps and bases exist in order to ensure that only the correct type of lamp can be used in a given situation (especially defined by the type of gear used in the particular luminaire).

The lamp caps of non-integrated compact fluorescent lamps are of the push-fit type (they fit by pushing them into the lamp holder). They are available in both square-shaped and rectangular-shaped versions. Lamp caps for lamps with an integrated starter employ two-pin connectors, while lamps for use with electronic control gear, or dimmers have four-pin connectors. Fig. 5.7 shows examples of two-pin and four-pin lamp caps.

Fig. 5.7 Examples of two-pin (top) and four-pin lamp caps for compact fluorescent lamps.

## 5.3 Performance characteristics

### 5.3.1 Energy balance

Fig. 5.8 shows the energy balance of a typical compact fluorescent lamp. It shows that approximately 20 per cent of the input power is emitted in the form of visible radiation. We saw earlier that a tubular fluorescent lamp emits some 28 per cent of visible radiation. The difference is largely due to the fact that in compact lamps the multitude of closely-packed tube parts absorb some of the light.

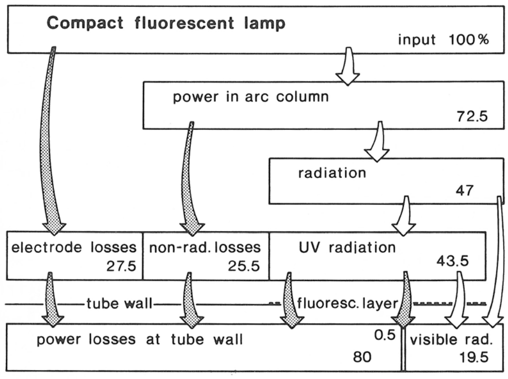



Fig. 5.8 Energy balance of a typical compact fluorescent lamp.

### 5.3.2 System luminous efficacy

The luminous efficacy of a compact fluorescent lamp is partly dependent on the wattage of the lamp and the colour quality of the light emitted, but more so on how and how many times the compact tube is folded. In low-wattage versions, good colour rendering versions have a system luminous efficacy starting at 45 lm/W, while higher-wattage versions reach efficacies of up to some 70 lm/W.

### 5.3.3 Lumen-package range

Compact fluorescent lamp with integrated control gear are produced in the range from some 250 to 2000 lumen (corresponding wattage range approx. 5 W to 35 W). Non-integrated types are available in the range from some 250 to 6000 lumen (corresponding wattage range approx. 5 W to 80 W).

### 5.3.4 Colour characteristics

The colour characteristics of compact fluorescent lamps are principally the same as those of normal fluorescent lamps. Reference on this point is therefore made to Section 4.3.4 of the section on tubular fluorescent lamps. The range of different colour temperatures and colour rendering indices available with compact fluorescents is, in practice, somewhat limited compared to that found with the very wide range of tubular lamps.

### 5.3.5 Lamp life

The lifetime of compact fluorescent lamps is very long compared with that of incandescent lamps, although it is usually shorter than that of tubular fluorescent lamps. Integrated versions (CFL-I) have, depending on type, a rated average lifetime of between 8 000 and more than 15 000 hours. Note that the life of retro-fit integrated CFLs is usually specified as rated average life (50 per cent mortality), as is the case with incandescent lamps (which have an average life of 1000 hours). Again, depending on type, non-integrated versions (CFL-NI) have economic lifetimes (based on 20 per cent mortality) of 7 000 to 20 000 hours..

### 5.3.6 Lamp price

CFL integrated lamps are three to ten times more expensive than GLS lamps (fifteen times more for dimmable versions). The price of non-integrated versions varies even more compared with that of GLS lamps because the range of lumen-outputs is so large. From low-lumen-package versions for domestic use to high-lumen-package versions (used in offices and in outdoor lighting) the price variation is between 1.5 and 20 times.

### 5.3.7 Lamp-lumen depreciation

The lamp-lumen depreciation of compact fluorescent lamps is similar to that of tubular fluorescent lamps. Reference is therefore made to Section 4.3.7 of the section on tubular fluorescent lamps.

### 5.3.8 Run-up and re-ignition

There are no fundamental differences here compared with normal fluorescent tubes. See Section 4.3.8.

### 5.3.9 Switching

There are no fundamental differences here compared with normal fluorescent tubes. See Section 4.3.9.

### 5.3.10 Dimming

Most integrated compact lamps are not dimmable. However, special, more-expensive versions, with standard Edison or bayonet cap, are produced that can be dimmed to approximately five per cent of full light output. Dimming of non-integrated, four-pin, compact lamps is possible, and is fundamentally the same as with normal fluorescent lamps (see Section 4.3.10).

### 5.3.11 Ambient-temperature sensitivity

With each different lamp shape the location of the coldest spot is also different, and this has consequences for the mercury pressure and therefore for the ambient-temperature sensitivity (See also text box of Section 4.3.11). With some shapes the coldest spot is also influenced by the burning position of the lamp (for example, base up or base down). The folded, integrated versions often use amalgam instead of pure mercury to stabilise the mercury pressure and thus to minimise the temperature sensitivity. The consequence of using amalgam is that the lamp, although igniting immediately, may take up to three minutes to give its normal light output.

### 5.3.12 Mains-voltage variations

No fundamental differences compared with normal fluorescent tubes. See Section 4.3.12.

## 5.4 Product range

Compact fluorescent lamps are being produced in many types with different properties. The more important lamp properties for which different versions are made are: gear integration (integrated or non-integrated) tube diameter (13 mm, S type; and 18 mm, L type), shape, tube length (related to lumen package), lamp circuit, colour temperature and colour rendering. Table 5.1 indicates for all these lamp aspects the range of lamp types available.

| Lamp Property | Range of lamp types |
|---|---|
| Gear integration | integrated (I)/non-integrated (NI) |
| Tube diameter | 13mm/18mm |
| Shape | Various, see Section 6.2.1 |
| Lamp length | 80mm - 200 mm (CFL-I)/100mm - 600mm(CFL-NI) |
| Lamp circuit | electromagnetic ("conventional")/HF electronic |
| Colour temprature Tk | standard range (2700K - 6000K) |
| Colour rendering Ra | Ra>90/80 < Ra <90 |

Table 5.1 Lamp properties versus lamp types.

# 6 Induction lamps

Induction lamps, like fluorescent lamps, belong to the family of low-pressure mercury gas discharge lamps. Unlike other discharge lamps they have no electrodes, which is why they are also called "electrodeless lamps". The consequence of having no electrodes is a very long economic life of around 60 000 to 75 000 hours. This long life is also the main feature of induction lamps. They find their application in situations where lamp replacement is near- impossible or very expensive. Philips was the first company to introduce induction lamps onto the market, under the name QL, in 1991.[8]

## 6.1 Working principle

In an induction lamp, the free-running electrons needed for the gas discharge are obtained by winding an induction coil around a ferrite core placed in or around a discharge vessel. In the case of the QL lamp, the coil is placed inside a bulb-shaped vessel (Fig. 6.1).[9]

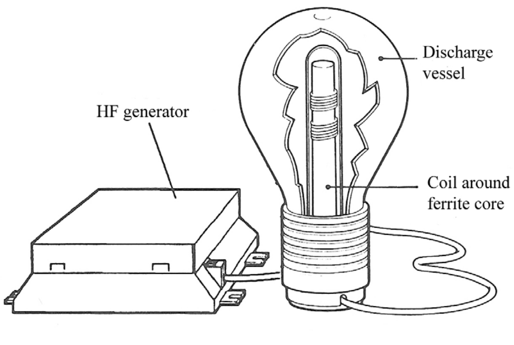



Fig. 6.1 The principal parts of an induction lamp.

The induction coil is connected to a high-frequency power source and acts like a primary winding in a transformer. In a transformer, an alternating current in a primary winding around an iron core creates an alternating magnetic field that in turn initiates an alternating current in a secondary coil wound around the primary coil (Fig. 6.2).

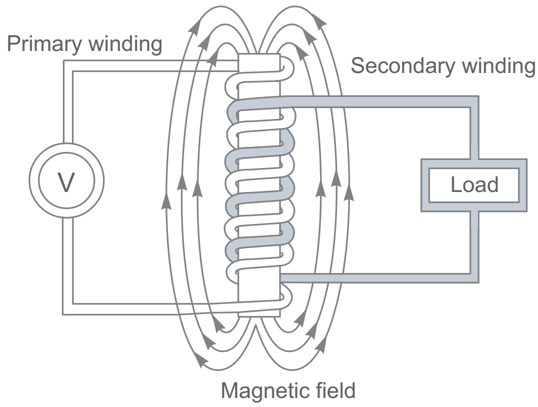



Fig. 6.2 Principle of a transformer

In the discharge vessel, the mercury gas surrounding the ferrite core acts as the secondary coil (since mercury is a metal). The secondary current initiated in the mercury consists of free- running electrons around the ferrite core (Fig. 6.3). As in a normal fluorescent gas discharge, these free-running electrons ionise and excite other mercury atoms, which results in the emission of the same radiation as in a tubular fluorescent lamp.

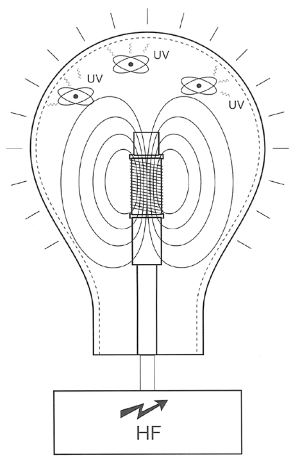



Fig. 6.3 Principle of an induction lamp.

Since the vessel's interior is coated with the same fluorescent powder as in normal fluorescent lamps, the same light is obtained. As mentioned at the beginning of this section, the main difference with normal fluorescent lamps is the extremely-long lifetime of induction lamps, since they have no electrodes. The high frequency of 2.65 MHz is generated by an electronic circuit.

8 In 1991 Philips celebrated its 100th anniversary.

9 The ferrite core with coil is called an antenna, just like those used in portable radios.

## 6.2 Lamp construction

The discharge vessel is made of the same type of glass as normal fluorescent tubes, and has a cylindrical glass cavity in which the antenna is positioned (Fig. 6. 4). The mercury in the vessel is present in the form of an amalgam, which is necessary for a stable operation of the lamp at the high operating temperature. Special precautions are taken in the design of the lamp to limit excessive heat build up around the antenna. The high-frequency power generator is connected to the antenna with a coaxial cable. The cable forms part of the electronic circuit and is therefore an integral part of the system (Fig. 6.5).

Some manufacturers have the coil with iron core around the outside of the discharge vessel, which then has a different, flatter shape than the pear-shaped version (Fig. 6.6).

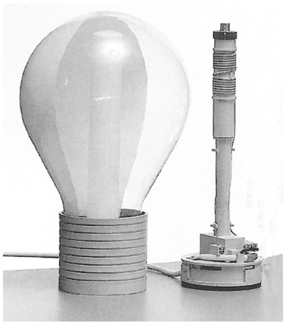


Fig. 6.4 Photograph of induction lamp vessel and antenna. The antenna is placed in the cylindrical cavity of the vessel. This lamp is only partly covered with fluorescent powder in order to show the cylindrical cavity.


Fig. 6.5 Pear-shaped induction lamp, QL, with internal antenna.

Fig. 6.6 Induction lamp with external antenna.

## 6.3 Performance characteristics.

### 6.3.1 Energy balance

Around 17 per cent of the input power of an induction lamp is radiated as visible light. The remaining part is lost as heat in the power generator, in the antenna, and in the discharge.

### 6.3.2 System luminous efficacy

The luminous efficacy of QL lamps is smaller than that of normal fluorescent lamps. It varies, depending on the wattage, between 65 lm/W and 75 lm/W.

### 6.3.3 Lumen-package range

The QL induction lamps are available in a lumen-package range from some 3500 to 12 000 lumen (corresponding wattage range 55 W to 165 W).

### 6.3.4 Colour characteristics

The fluorescent coating is of the same composition as that in normal fluorescent tubes, so the colour characteristics are also the same. See Section 4.3.4.

### 6.3.5 Lamp life

The lamp life of most induction lamps is extremely long. Based on a mortality rate of 20 per cent, QL lamps have a lifetime of between 60 000 and 75 000 hours. This is almost seven years of continuous operation, day and night.

### 6.3.6 Lamp price

Induction lamps are expensive: some 70 to 100 times more so than GLS lamps. But this high lamp price has to be balanced against the extremely-long lifetime of these lamps. This means that where lamp replacement is difficult, very expensive, or even impossible, the balance will certainly be in favour of the longer life of these lamps.

### 6.3.7 Lamp-lumen depreciation

Lumen depreciation in induction lamps is determined by a decrease in the activity of the fluorescent powder. At 60 000 hours the depreciation is around 25 per cent, which is why this lifetime figure is quoted. The actual life of QL lamps is usually much longer.

### 6.3.8 Run-up and re-ignition

A high-voltage ignition pulse produced by the HF generator ignites the lamp within five seconds, after which it emits its full light output within one minute. Thanks to the high-voltage ignition pulse, hot re-ignition of the lamp is immediate.

### 6.3.9 Dimming

Most standard versions of induction lamps are not dimmable. However, some special versions, which are dimmable to 50 per cent, are available for use in road lighting.

### 6.3.10 Ambient-temperature sensitivity

Amalgam is used instead of pure mercury to keep the sensitivity to ambient temperatures within practical limits. Lamp position sometimes plays a role in this as well. It is therefore important to follow the recommendations from the lamp manufacturer with respect to the luminaire design

## 6.4 Product range

Induction lamps are available in versions with internal (QL) and external antenna. The corresponding shapes, as we have seen, are pear shaped and plane (Figs 6.5 and 6.6). They are normally available in colour-rendering types 800 and 900, with colour temperatures of 3000 K and 4000 K.

#  7 Low-pressure sodium lamps

Low-pressure sodium lamps belong to the group of High-Intensity Discharge (HID) lamps, because they are available in high-light output (and thus high-luminous-intensity) versions.

All low-pressure gas discharge lamps have in common the fact that they are long. Like the tubular-fluorescent lamp, which belongs to the family of low-pressure mercury lamps, low-pressure sodium lamps are also long. They are highly-efficient lamps with a good lifetime but no colour rendition at all. Their application is therefore restricted to those situations where colour rendering is of no importance, as for example on motorways, railway-marshalling yards and in some security-lighting situations.

The Philips designation for low-pressure sodium lamps is SOX, where "SO" stands for sodium. Low-pressure sodium lamps are sometimes also referred to as LPS lamps.

### 7.1 Working principle

The gas discharge principle of low-pressure sodium lamps is similar to that of low-pressure mercury lamps. In the former, the discharge takes place in vaporised sodium.[10]

The low-pressure sodium discharge emits monochromatic radiation in the visible range. Therefore, unlike low-pressure mercury lamps, they do not need fluorescent powders to convert the wavelength of the radiation. The monochromatic (single wavelength) radiation is the reason that colour rendering is non-existent. The wavelength of the monochromatic radiation is 589 nm (yellowish light), which is very close to the wavelength for which the eye has its maximum sensitivity (Fig. 7.1). It is mainly for this reason that the lamp has such an extremely-high luminous efficacy (up to 190 lm/W).

Like all gas discharge lamps (with very few exceptions), a low-pressure sodium lamp cannot be operated without a ballast to limit the current flowing through it.

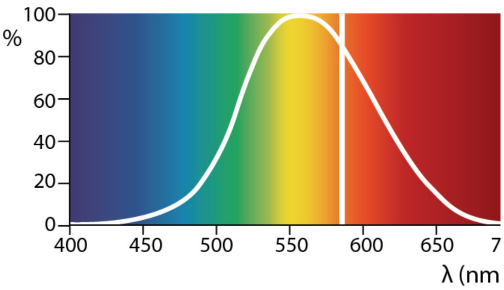



Fig. 7.1 Eye-sensitivity curve and the monochromatic line of 589 nm of the low-pressure sodium spectrum.

### 7.2 Lamp construction

The main parts of a low-pressure sodium lamp are (Fig. 7.2):

- discharge tube
- fill gas
- electrodes
- outer bulb with inner coating
- lamp cap

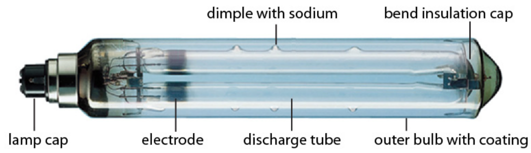



Fig. 7.2 Principle parts of a low-pressure sodium-discharge lamp (SOX).

#### 7.2.1 Discharge tube

Just as with the fluorescent lamp, the power dissipated in this lamp largely determines the length of the discharge tube. Especially for the higher wattages (and thus lumen packages), the unfolded length has to be really long. To reduce the actual length of the lamp, the discharge tube of low- pressure sodium lamps is therefore always U-shaped. Nevertheless, the highest lumen packages still require a lamp length of about 1.2 m.

The U-shaped discharge tube is made of sodium-resistant glass and contains a number of small dimples, or hollows, where the sodium is deposited as a liquid during manufacture. After ignition, the discharge first takes place through the inert gas mixture. As the temperature in the tube gradually

10 Under-operating conditions the sodium vapour has a pressure of about 0.7 Pa (7.10-6 atm.).

increases, some of the sodium in the dimples vaporises and takes over the discharge, which then emits the monochromatic radiation. At switch-off, the sodium condenses and again collects at the dimples, these being the coldest spots in the tube (just as water vapour condenses on the cool windows of a room). Without the dimples the sodium would, after some switch-on switch-off cycles, gradually condense along the whole inner tube wall, decreasing light transmission considerably.

### 7.2.3 Fill gas

The inert gas mixture of neon and argon, called the "Penning mixture", acts as a starting gas and buffer gas (to protect the electrodes). During start-up, the discharge only takes place in this gas, which is why a low-pressure sodium lamp radiates deep-red light for some 10 minutes during start-up (Fig. 7.3).

Fig. 7.3 Immediately after switch-on, a low-pressure sodium lamp emits just a little reddish light, which gradually changes to the familiar yellow sodium light when the lamp has fully warmed up.

### 7.2.4 Electrodes

Most modern low-pressure sodium lamps have cold-start electrodes. These consist of a triple-coiled tungsten wire, so that they can hold a large quantity of emitter material.

### 7.2.5 Outer bulb

The optimum sodium-vapour pressure is reached when the temperature of the wall of the discharge tube is maintained at 260°C. To reach this temperature efficiently, the U-shaped discharge tube is contained in an evacuated outer-glass tube. To further increase the thermal insulation, this outer tube is coated on its inner surface with an interference layer that reflects infrared radiation but transmits visible radiation. In this way, most of the heat radiation is reflected back into the discharge tube, so maintaining the tube at the desired temperature, whilst visible radiation is transmitted through the layer.

As we have seen earlier, this principle of infrared reflective interference layers is also used in a special type of halogen lamp (Section 3.1.3 "Infrared-reflective-coating technology").

In the past, before infrared reflection coatings were employed, low-pressure sodium lamps used an evacuated double-walled tube (vacuum-flask principle), which was detachable and could be re-used after lamp replacement.

Apart from the dimples, the bend of the U-tube also forms a cold spot where sodium can condense and accumulate. The bend is therefore insulated by a heat-reflecting metal cap.

Even small quantities of oxygen or water vapour could shorten the lifetime of the tungsten wire through corrosion. An absorbent "getter" is therefore added to remove this oxygen or water vapour.

### 7.2.6 Lamp cap

All SOX lamps are provided with a bayonet-type lamp cap (Fig. 7.4). This allows the discharge tube to be accurately positioned. This is critical, because the light distribution of a low-pressure sodium luminaire is dependent on the position of the U-shaped discharge tube.

Fig. 7.4 Bayonet lamp cap that accurately positions the U-shaped discharge tube in the luminaire.

## 7.3 Performance characteristics

### 7.3.1 Energy balance

Fig. 7.5 shows the energy balance of a typical low-pressure sodium lamp. It shows that approximately 40 per cent of the input power is emitted in the form of visible radiation. This is the highest percentage of all gas discharge lamps. The remaining part of the input power is lost in the form of heat.

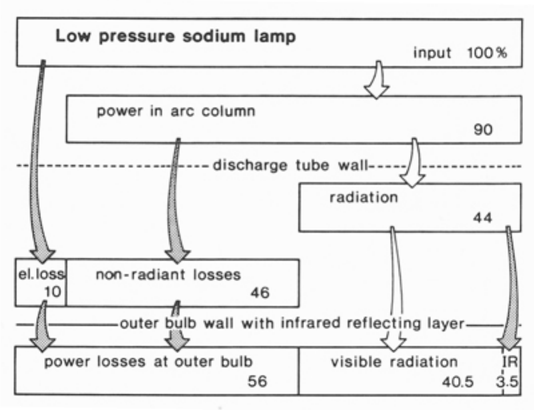



Fig. 7.5 Energy balance of a typical low-pressure sodium lamp.

### 7.3.2 System luminous efficacy

The luminous efficacy of the system is strongly dependent on the wattage of the lamp, and ranges from 70 lm/W to 190 lm/W, for low and high wattages, respectively.

### 7.3.3 Lumen-package range

Low-pressure sodium lamps are available in the range from approximately 2000 to 30 000 lumen (corresponding wattage range: 18 W to 180 W).

### 7.3.4 Colour characteristics

As mentioned before, low-pressure sodium lamps emit monochromatic light in the yellowish part of the spectrum (Fig 7.6). Colour rendering is therefore non-existent (Ra = 0). The correlated colour temperature is around 1700 K.

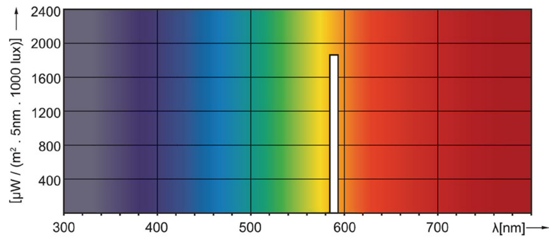



Fig. 7.6 Spectral energy distribution of low-pressure sodium lamps.

### 7.3.5 Lamp life

Apart from the normal cause of failure in gas discharge lamps (viz. electrode emitter exhaustion), low-pressure sodium lamps may also fail because of cracks or leaks in the long discharge tube or outer bulb. This may especially be the case in environments where there are strong vibrations – as for example may occur in poorly-designed road-lighting luminaires during strong winds. Leakage in the outer bulb disrupts the thermal isolation, which in turn means that not enough sodium will vaporise. As a consequence, the discharge will take place in the starting- gas mixture, so emitting only the corresponding deep red light.

Economic lamp life is around 12 000 hours (based on a 20 per cent mortality rate). Some versions make use of special getter material to maintain a high vacuum, resulting in fewer failures during the economic lifetime of the lamp: the economic lamp lifetime is about 15 000 hours (again: mortality rate of 20 per cent).

### 7.3.6 Lamp price

From low wattage (18 W) to high wattages (131 W and 180 W), the price of low-pressure sodium lamps is a factor 10 to 30 higher than that of GLS lamps.

### 7.3.7 Lamp-lumen depreciation

Lumen depreciation occurs through blackening of the discharge tube by scattering of the emitter material of the electrodes and by discolouration of the glass caused by the sodium. Depending on the type of control gear used, these effects are partially counteracted by a slow and gradual increase in the power dissipated in the lamp.

### 7.3.8 Burning position

Electrodes and lead-in wires coming into contact with condensed sodium can eventually suffer damage. To prevent this from happening, low-pressure sodium lamps have restrictions as to their burning position. Base-down burning positions in particular have to be avoided under all circumstances. Fig. 7.7 shows the permissible burning positions for Philips low-pressure sodium lamps. As can be seen, the restrictions are less critical for lower-wattage (viz. smaller) lamps, simply because they contain less sodium.

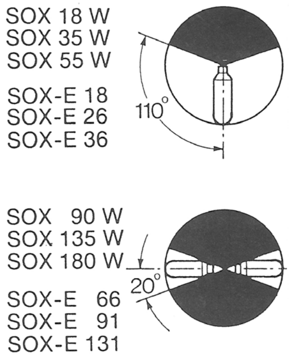



Fig. 7.7 Permissible burning positions of low-pressure sodium lamps.

### 7.3.9 Run-up and re-ignition

As has already been explained, the sodium needs time to vaporise while the discharge takes place in the starting-gas mixture. The warming-up process takes about 10 minutes. Nearly all low-pressure sodium lamps re-ignite immediately. The exceptions are the high-wattage (131 W and 180 W) lamps, which restrike after 10 minutes.

### 7.3.10 Dimming

Low-pressure sodium lamps cannot be dimmed. Dimming would decrease the lamp temperature so that not enough sodium would remain in the vapour state to maintain the sodium discharge.

### 7.3.11 Ambient-temperature sensitivity

The good thermal insulation afforded by the outer bulb ensures that lamp performance is almost independent of ambient temperature. Also, thanks to the starting-gas mixture, starting too is almost independent of ambient temperature.

### 7.3.12 Mains-voltage variations

The variations in lamp current and lamp voltage as a consequence of a change in mains supply voltage tend to cancel each other out, the net result being that the lamp wattage, and to a certain extent the luminous flux, remain practically constant over a wide range.

## 7.4 Product range

Just like TL5 tubular-fluorescent lamps, low-pressure sodium lamps are available in two versions, each with a different balance between efficacy and lumen output. The Philips names for these two types of low-pressure sodium lamps are SOXI (the high-lumen-output version) and SOX-E (the high-efficacy version). Length-for-length, the luminous efficacy of the SOX-E series is some 10 to 15 per cent higher than that of the SOX series, while the light output is some 20 per cent less. SOX-E lamps can be operated on HF electronic control gear, which further increases their efficacy by between 15 and 35 per cent. The length of the SOX lamp increases considerably with wattage: the 18 W version (which is also known as the mini-SOX) has a length of 22 cm, while the 131 W and 180 W versions both have a length of 112 cm (Fig. 7.8).

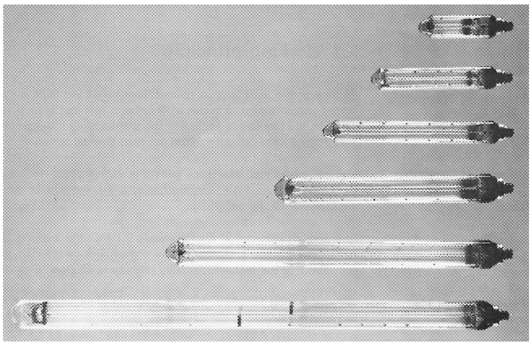


Fig. 7.8 The range of low-pressure sodium lamps (SOX-E) from 18 W to 131 W.

# 8 High-pressure mercury lamps

High-pressure mercury lamps belong to the group of High Intensity Discharge (HID) lamps. High-pressure mercury lamps are available in versions where the discharge takes place in vaporised mercury only (Philips designation: HPL) and in versions in which metal halides are added so that the discharge takes place in mercury vapour and in vaporised metals from the metal-halide components. These latter types are called metal halide (or HPI) lamps. Given the special operating principle and construction of metal halide lamps, they will be dealt with in a separate section (Section 9).

High-pressure mercury lamps, like all high-pressure discharge lamps, are compact compared to low-pressure discharge lamps. HPL lamps have a moderate efficacy and moderate colour rendering. With their cool-white light they were extensively used in road lighting, especially in built-up areas. Since the introduction of the more efficient high-pressure sodium lamps in the late 1960's, these lamps have in many cases replaced normal high-pressure mercury lamps.

## 8.1 Working principle

The gas discharge principle of high-pressure mercury lamps is similar to that of all other gas- discharge lamps. In high-pressure mercury lamps the discharge takes place in vaporised mercury at a pressure of around 106 Pa (10 atmospheres). The spectrum is a line spectrum with emissions in the long-wave UV region and in the visible region at the yellow, green, blue and violet wavelengths. The lamp without fluorescent powder lacks red in its spectrum and has a bluish-white colour appearance and very poor colour rendering. In most high-pressure mercury lamps, fluorescent powders are used to improve the colour quality by converting a large part of the (small) UV component into visible radiation, predominantly in the red end of the spectrum (HPL lamps). The result is cool-white light of moderate colour rendering and improved efficacy.

> In high-pressure mercury lamps, fluorescent powder is often employed to improve the colour of the light. In contrast with low-pressure mercury tubular and compact fluorescent lamps, the conversion of UV into visible in high-pressure mercury lamps does little to increases their efficacy (only some 5 per cent).

## 8.2 Lamp construction

The main parts of a high-pressure mercury lamp are (Fig. 8.1):

- discharge tube
- fill gas
- electrodes
- outer bulb with fluorescent coating
- lamp cap

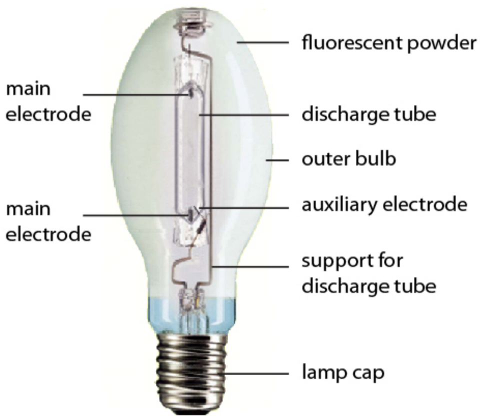



Fig. 8.1 Principle parts of a high-pressure mercury gas discharge lamp (HPL).

### 8.2.1 Discharge tube

In view of the high operating temperature, quartz is used for the discharge tube.

### 8.2.2 Fill gas

The discharge tube contains a small quantity of mercury (which completely evaporates during operation) and an inert gas filling.

### 8.2.3 Electrodes

The main electrodes consist of a core of tungsten rod with a tungsten coil (impregnated with emissive material) wound around it. To aid starting, a normal high-pressure mercury lamp has not only an inert gas but also an auxiliary electrode. Because of this, a normal mercury lamp does not need an external igniter. The auxiliary electrode simply consists of a tungsten wire positioned very close to one of the main electrodes (Fig. 8.2)

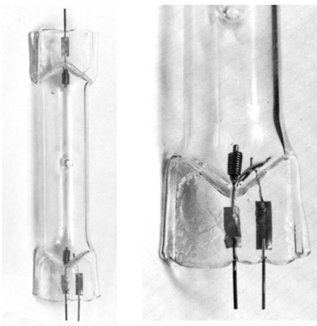


Fig. 8.2 Discharge tube: on the right an enlargement, showing the auxiliary electrode and one main electrode.

## 8.2.4 Outer bulb

An outer bulb (usually ovoid in shape) with an inert gas filling isolates the gas discharge tube so that changes in ambient temperature have no influence on its proper functioning. It also protects the lamp components from corrosion at the high operating temperatures involved. For the smaller lamps, with their lower operating temperatures, normal glass is used, while for the other types hard glass is used.

## 8.2.5 Fluorescent powder

As has already been mentioned, high-pressure mercury lamps usually employ fluorescent powder to improve the colour quality of the light emitted. The powder is provided as a coating on the inner surface of the outer bulb. Different fluorescent coatings are used to obtain different lamp types with different colour qualities and lamp efficacies.

## 8.2.6 Lamp cap

Lamp caps are of the Edison-screw type, with the wattage of the lamp determining their size (E27 and E40).

## 8.3 Performance characteristics

## 8.3.1 Energy balance

Fig. 8.3 shows the energy balance of a typical high-pressure mercury lamp. It shows that approximately 17 per cent of the input power is emitted in the form of visible radiation. Compare this with what we have seen before with a tubular fluorescent lamp (28 per cent), a compact fluorescent lamp (20 per cent) and a low-pressure sodium lamp (40 per cent).

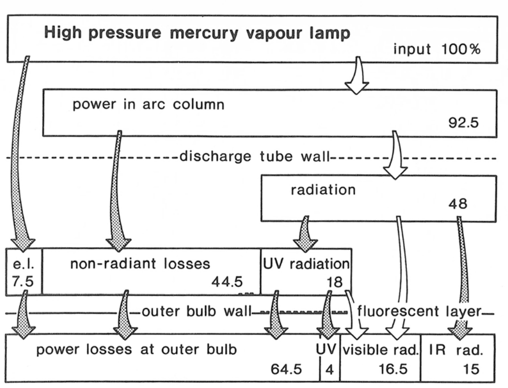



Fig. 8.3 Energy balance of a typical high-pressure mercury lamp (HPL).

## 8.3.2 Luminous efficacy

Luminous efficacy varies with lamp wattage and with the colour quality of the lamp from some 35 lm/W to 60 lm/W.

## 8.3.3 Lumen-package range

High-pressure mercury lamps are produced in lumen packages between some 2000 and 60 000 lumen (corresponding wattages between 50 W and 1000 W).

## 8.3.4 Colour characteristics

As has already been mentioned, high-pressure mercury lamps have a line spectrum (Fig. 8.4). The two lines in the red part of the spectrum are obtained by conversion of ultraviolet radiation by the fluorescent powder. The colour characteristics are dependent on the composition and quality of the fluorescent powders used. Different compositions and qualities are used to produce lamps with colour temperatures between some 3500 K and 4500 K, with colour-rendering index (Ra ) values of around 60 for high-quality versions and around 40 for ordinary versions.

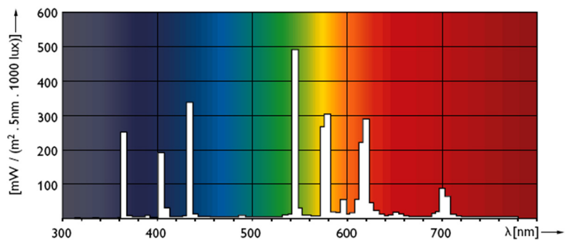



Fig. 8.4 Spectral energy distribution of a high-pressure mercury lamp (HPL-N)

### 8.3.5 Lamp life

As with most gas discharge lamps, lamp life is determined by emitter exhaustion. Economic life varies according to type between 10 000 and 15 000 hours (20 per cent mortality).

### 8.3.6 Lamp price

High-pressure mercury lamps are, depending on their wattage, six to forty times more expensive than GLS lamps.

### 8.3.7 Lamp-lumen depreciation

Lamp-lumen depreciation is caused by evaporation and scattering of electrode material (lamp blackening) and by the gradual decrease in the activity of the fluorescent powder. The point at which 20 per cent lumen depreciation occurs lies at around 10 000 to 15 000 hours.

### 8.3.8 Run-up and re-ignition

The run-up time of a high-pressure mercury lamp to its full temperature and corresponding nominal mercury pressure is some four minutes. The hot lamp will not restart until it has cooled sufficiently to lower the vapour pressure to the point at which re-strike with the voltage available is possible. The re-ignition time is in the order of five minutes.

### 8.3.9 Dimming

High-pressure mercury lamps cannot be dimmed.

### 8.3.10 Mains-voltage variations

A five per cent variation in the mains voltage changes both lamp current and light output by ten per cent. Over-voltage decreases lamp life and increases lamp depreciation because of the correspondingly higher current.

## 8.4 Product range

High-pressure mercury lamps are available in an ordinary version with poor colour rendering (Ra of around 40), and in so-called comfort versions with an improved colour rendering of around 60. The bulb is ovoid in shape and increases in size with increase in wattage (Fig. 8.5). Reflector lamp versions are produced with a cone-shaped outer bulb and an internal reflective coating on the front (Fig. 8.6).

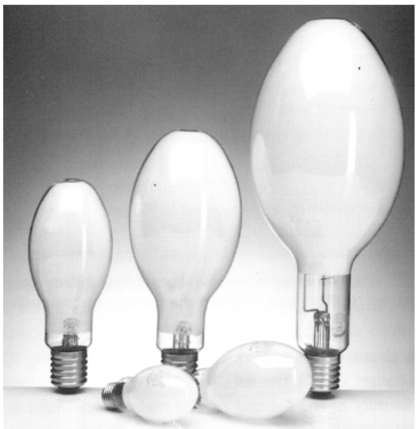


Fig. 8.5 Different-wattage high-pressure mercury HPL lamps.

Fig. 8.6 Different-wattage reflector high-pressure mercury lamps.

There is one version of the high-pressure mercury lamp, the “blended light lamp”, that does not need an external ballast. The ballast has simply been built into the lamp itself in the form of a tungsten filament. The lamp can be connected direct to the mains. The light from the mercury discharge and that from the heated filament blend together (hence the name blended light lamp). The colour characteristics of this lamp are therefore better than those of a normal high-pressure mercury lamp, but this comes at the cost of a considerably lower efficacy.

# 9 Metal halide lamps

Metal halide lamps are high-pressure mercury lamps that contain metal halides in addition to the mercury. In the heated discharge tube, the metals of the halides take part in the discharge process and radiate their own spectrum.[11] Compared with high-pressure mercury lamps, both colour properties and efficacy are considerably improved. Thanks to the fact that no fluorescent powder is needed, the small gas discharge tube itself is the light-emitting surface. This small light-emitting surface makes the lamps extremely suitable for use in reflector and floodlight luminaires. Originally, they were solely produced in extremely-high lumen packages with relatively large lamp dimensions (about the size of a 1 litre bottle). These lamps are particularly suited for use in floodlights for the lighting of stadiums. Today, compact metal halide lamps are available in small lumen packages, which makes them very suitable for use in compact reflector luminaires for accent lighting both indoors and outdoors. These versions have become an energy-efficient alternative for halogen lamps. Special compact metal halide versions are being produced for use in film studios and theatres. The smallest metal halide lamps are used for car headlamps (these are the so-called xenon lamps, whose gas discharge tube is no larger than a match head). Philips designations for the different types of metal halide lamps are HPI, MHN, CDM, CPO, Mastercolour and Cosmopolis. Metal halide lamps belong to the group of high-intensity discharge (HID) lamps.

## 9.1 Working principle

Suitable metals that vaporise in the hot discharge tube so as to contribute to the discharge process cannot be added directly to the mercury in the discharge tube. This is because metals suitable for this purpose attack the wall of the discharge tube at the high temperatures that are needed for the gas discharge to occur. The solution to this problem has been found to add these metals in the form of their non-aggressive chemical compounds with a halogen (iodine, bromide or chloride), hence the name metal halide lamps. The solid metal halides start evaporating after switching on the lamp, once the mercury discharge has increased the temperature in the discharge tube sufficiently. When this vapour enters the area of the mercury discharge in the centre of the tube with its very high temperature (around 3000°C), it dissociates into its separate elements: metals and halogen. There the metals in their pure, vaporised state, take part in the discharge process and determine the efficacy and colour characteristics of the radiation. The aggressive vaporised metal cannot reach the tube wall because at the lower wall. [12]

## 9.2 Lamp construction

The main parts of a metal halide lamp are (Fig. 9.1):

- discharge tube
- metal-halide additives
- fill gas
- outer bulb
- electrodes
- lamp cap

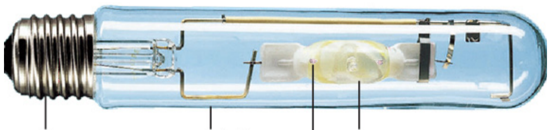



Fig. 9.1 Main parts of a metal halide lamp (example HPI-T).

### 9.2.1 Discharge tube

The discharge tube is made of either quartz or a ceramic material. Some metals of the metal- halide compounds (especially sodium) have the tendency, at high temperatures, to migrate slowly through the quartz wall of the tube, with the result that there is a gradual change in the colour properties of the lamp during its lifetime. The use of ceramic discharge ttubes solves the problem. Such tubes are impervious to these metals, even at high operating temperatures. Later we will see that high-pressure sodium lamps make use of the same ceramic material. Metal halide lamps using ceramic material have the Philips designation CDM lamps. Fig. 9.2 shows examples of both quartz and ceramic gas discharge tubes.

Fig. 9.2 Gas discharge tube made of quartz (HPI-T lamp) and ceramic (CDM lamp) respectively. The yellow material seen through the quartz tube is condensed metal halide.

11 In fact metals are used that excite easier than does mercury. This means that mercury in a metal halide lamp does not take part in the generation of light but serves to keep the discharge going through a process of heat and voltage regulation (buffer gas).

12 Note the great similarity of this process with the halogen cycle process that is used in normal halogen incandescent lamps (Section 3.1.1)

The ceramic material (PolyCrystalline Alumina, or PCA) cannot be softened and worked as can glass or quartz. A ceramic discharge tube is therefore built up from a hollow ceramic cylinder that is closed by gluing circular ceramic flat plates (discs) on its two ends (Fig. 9.3). Ceramic discharge tubes can be constructed to better tolerances than can quartz tubes. Since the ceramic tube is produced by sintering minuscule aluminium-oxide particles one cannot look straight through the wall, although the light transmittance is more than 90% (compare this effect with a broken and fragmented car window: light passes through it, although one gets no sharp image when looking through it). We then speak of translucent instead of transparent material.

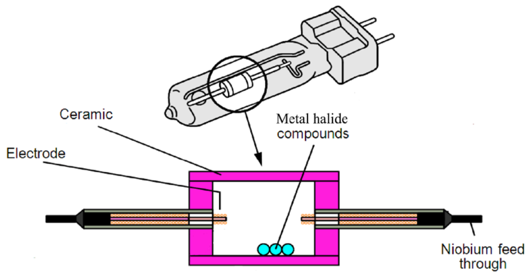



Fig. 9.3 Schematic view of a ceramic discharge tube.

Ceramic gas discharge tubes are operated at a higher temperature than are quartz tubes. The higher operating temperature influences the spectrum of the radiation. The result is a lower colour temperature compared to that of quartz metal halide lamps, and a 10 per cent higher efficacy.

### 9.2.2 Metal halides additives

In theory, some fifty different metals can be used for metal halide compounds, and different manufacturers have introduced various combinations of these metals. Examples of some of the metals used in metal halide compounds are: sodium, thulium, thallium, indium, scandium, dysprosium and tin. Some of these metals belong to the group of elements called rare earth metals. Most lamps use a mixture of at least three different metal halides. Each different combination results in a different spectrum, but also in different efficacy, lumen maintenance and lifetime characteristics.

### 9.2.3 Fill gas

Besides metal halides and mercury, an inert gas is also added to the discharge tube, like in most other discharge lamps.

### 9.2.4 Electrodes

The electrodes of metal halide lamps are of the type used in normal high-pressure mercury lamps. They consist of a tungsten rod, with a tungsten coil impregnated with emissive material, wound around it. They are of heavier construction because of the higher operating temperature.

### 9.2.5 Outer bulb

Most metal halide lamps use a hard-glass or (for very compact versions) quartz outer bulb for protection and for heat insulation of the discharge tube (Fig. 9.4). They may be evacuated or gas filled. In the case of quartz outer bulbs a UV-blocking quartz is used to limit harmful UV radiation. For the same reason, some hard-glass versions use a cylindrically-shaped UV-block shield around the discharge tube (Fig. 9.5). Both single-ended and double-ended outer bulbs are used.

Fig. 9.4 Hard glass, single-ended (top) and quartz, double-ended outer bulbs.

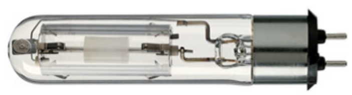


Fig. 9.5 Hard glass, single-ended outer bulb with UV-block shield around the discharge tube.

The inner wall of the outer bulb reflects a very small part of the light that consequently cannot be very well controlled by a luminaire reflector. But since the reflected amount is so small, this is normally not a problem, except where very-high-lumen-output lamps are employed. However, in floodlight installations, a very small amount of uncontrollable light could give rise to disturbing light pollution. For these applications special lamps are therefore available that have no outer bulb (Fig. 9.6). Some of these have short-arc gas discharge tubes to allow of optimised beam control in all directions. For reasons of thermal stability and safety, those lamps without an outer bulb must be used in specially-designed luminaire housings.

Fig. 9.6 Double-ended quartz metal halide lamp (short arc) not making use of an outer bulb (MHN-SA).

### 9.2.6 Lamp caps

Metal halide lamps come with a great variety of lamp caps. The single-ended lamps of higher wattage have in general E40 Edison screw caps. Some caps have special electrical insulation because of the high ignition pulses (between 600 V and 5000 V). The lower-wattage single-ended lamps have two-pin electrical connections of various types, sometimes with ceramic electrical insulation (Fig. 9. 7). In order to be able to exactly position the gas discharge arc in a luminaire, some lamps are provided with a so-called pre-focussed lamp cap (Fig. 9.7, right). The double-ended lamps use lamp caps of the type that are also used in double-ended halogen lamps (Fig 9.4, bottom ). The lamps without an outer bulb again have different lamp caps, as shown in Fig. 9.6.

Fig. 9.7 Various lamp caps for compact single-ended metal halide lamps.

## 9.3 Performance characteristics

### 9.3.1 Energy balance

Fig. 9.8 shows the energy balance of a metal halide lamp type that belongs to the middle range as far as efficacy is concerned. Almost 25 per cent of the input power is emitted in the form of visible radiation.

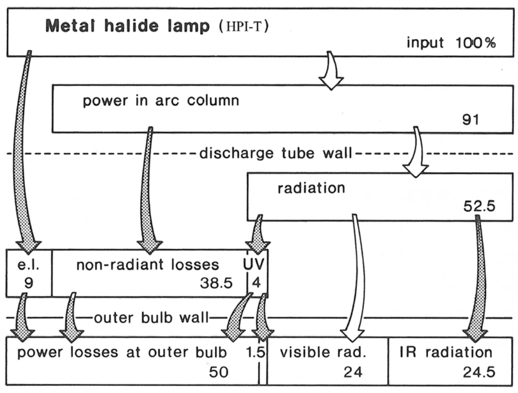



Fig. 9.8 Energy balance of a metal halide lamp (HPI-T).

### 9.3.2 System luminous efficacy

The compact versions of the metal halide lamp have lumen efficacies (depending on the metal halide mixture and gas discharge tube material used) of between 70 lm/W and 95 lm/W. When comparing this with normal halogen incandescent lamps with their maximum efficacy of 25 lm/W, it is clear that compact metal halide lamps are often very suitable to replace halogen lamps. The larger versions of metal halide lamps have efficacies from some 75 lm/W to slightly more than 105 lm/W.

### 9.3.3 Lumen-package range

Compact versions are available in lumen packages from some 1500 to 25 000 lumen (corresponding wattage range 20 W - 250 W). Larger versions range from some 20 000 lumen to more than 200 000 lumen (corresponding wattage range 250 W - 2000 W). Special (compact) types for use in film studios, theatres and professional photography are produced in lumen packages of up to more than 1 000 000 lumen (12 000 W).

### 9.3.4 Colour characteristics

As has been explained in the Sections above, by employing different metal-halide mixtures, lamps with different spectra can be produced. Like all gas discharge lamps, the metal halide lamp has a discontinuous spectrum. Figs 9.9 to 9.11 show the spectra of some typical metal halide lamps with different colour temperatures CCT and colour rendering index Ra. The same colour designation system is used as with fluorescent lamps.

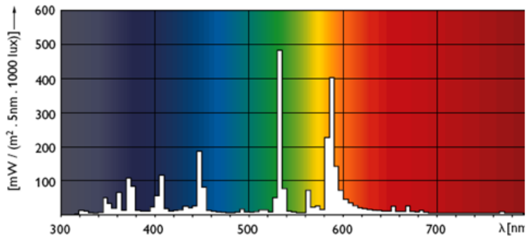



Fig. 9. 9 Spectral energy distribution of a metal halide lamp, colour type 642: Tk 4200 K and $R_a$ 65 (HPI).

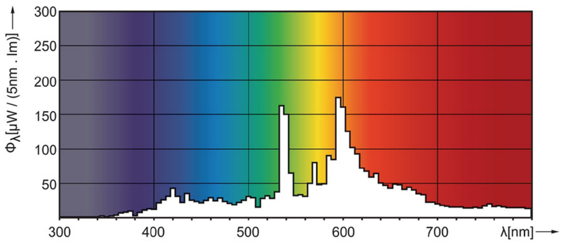



Fig. 9.10 Spectral energy distribution of a metal halide lamp, colour 830: Tk 3000 K and Ra 80 CDM).

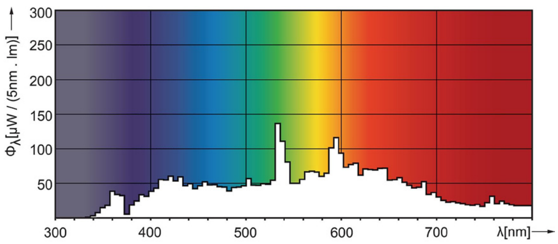



Fig. 9.11 Spectral energy distribution of a metal halide lamp, colour 942: Tk 4200 K and $R_a$ 90 (CDM).

Compact metal halide lamps are normally produced in the colour temperature range of 3000 K to some 4500 K, in two colour-rendering varieties: Ra ca. 80 and ca. 90. The larger metal halide lamps are available in the colour temperature range from approximately 4000 K to 6000 K, with colour rendering Ra in the range from 65 to more than 90. The special, daylight, metal halide lamp types for film studio and theatre lighting have high colour temperatures of between 6000 K and 8000 K with colour rendering values Ra between 65 and more than 90.

### 9.3.5 Lamp life

The lamp life of most metal halide types is somewhat shorter than that of other gas discharge lamps. This is because the electrodes are heated to a higher temperature with a correspondingly higher evaporation rate, and are gradually degraded and destroyed by chemical reactions with the metal halides. We have also seen that different metal halide lamp types employ widely-different construction methods. As a consequence, lamp life varies strongly with type. The economic life of compact versions lies between some 7000 and 14 000 hours (20 per cent mortality). The high-lumen-package versions vary from 4000 hours (single-envelope types for stadium floodlighting) to some 10 000 hours (again 20 per cent mortality). [13]

Those ceramic metal halide lamps specifically developed for use in road lighting (Philips designation Cosmopolis), where lights may be used 4000 hours a year, have lifetimes up to 20 000 hours (20 per cent mortality).

### 9.3.6 Lamp price

Compact metal halide lamps are, depending on their construction and complexity, a factor 10 to 40 more expensive than GLS lamps. With non-compact metal halides lamps this factor varies, according to wattage, by a factor of between 25 and 70, whereas for the special lamps for the lighting of sports arenas the factor can go up to approximately 150.

### 9.3.7 Lamp-lumen depreciation

Metal halide lamps have a higher lumen depreciation than most other discharge lamps. This is because of the higher degree of blackening from evaporated electrode material. Here too, the type of construction and sort of metal halides used play a role. Lumen depreciation values vary between some 20 and 30 per cent (after 10 000 hours). Some special types, such as those employed in road lighting, depreciate less rapidly (some 10 per cent after 10 000 hours).

### 9.3.8 Burning position

With the larger gas discharge tubes in particular, the burning position may affect the actual location of the various metals in the tube. This means that different burning positions may result in different colour shifts. Also, with some types of lamp construction, the burning position can influence the lifetime of the lamp: for example, because of attack of the electrodes by some of the metals of the halides. Many metal halide lamps therefore have restrictions as to their permitted burning position (although these are, of course, specified in their accompanying documentation). Compact, single-ended types, with either quartz or ceramic tube, have universal burning positions.

### 9.3.9 Run-up and re-ignition

The metal halides in the discharge tube need time

13 The lighting in most stadiums is used much less than 500 hours a year. For this application, 4000 hours lamp lifetime in practice means many, many years.

to heat up, evaporate, and dissociate into metal and halide. During this process, which takes about two to three minutes, the light output and colour gradually change until the final stable condition is reached. If there is an interruption in the power supply, medium and high-wattage lamps will take approximately 10 to 20 minutes for the pressure in the lamp to decrease enough for it to re-ignite. Compact ceramic lamps reignite much faster: after some 3 to 5 minutes. [14]

### 9.3.10 Dimming

TThe dimming of metal halide lamps is difficult because with the resulting decrease in temperature some of the metal halides condense, changing the constitution of the metal halides actually participating in the discharge. This in turn changes the colour properties of the light. By employing a specially-shaped burner, electronically-driven lamp versions have been developed that can be dimmed to some 50 per cent without suffering from this problem.

### 9.3.11 Ambient-temperature sensitivity

The very high operating temperature of metal halide lamps is not influenced by variations in ambient temperature. Consequently, the lumen output and colour quality of these lamps are also not influenced by ambient temperature.

### 9.3.12 Mains-voltage variations

Mains-voltage variations affect lumen output, lifetime and light colour. A mains voltage that deviates 10 per cent from its nominal value will result in perceivable colour shifts. Thanks to the higher operating temperature of ceramic lamps the effect on colour change is here considerably smaller. Both up and down variations in the mains shorten lamp life.

## 9.4 Product range

Metal halide lamps are available in a wide variety of types for many different applications, including floodlighting, road lighting, accent lighting (both interior and exterior), car headlamps and film-studio lighting. The more important lamp parameters, together with the corresponding range for which different versions are made, are listed in Table 10.1. Fig. 9.12 shows some examples of lamp types used mainly in indoor lighting, while Fig. 9.13 shows those types especially used in outdoor lighting.

| Lamp parameter | Range |
|---|---|
| Lamp size | medium/compact/very compact |
| Discharge-tube material | quartz/ceramic |
| Lamp shape | single ended/double ended |
| Outer bulb | outer bulb/coated outer bulb/no outer bulb |
| Lumen package | large/small |
| Lamp circuit | elctromagnetic (“conventional”)/HF electronic |
| Colour temprature Tk | 3000 - 4000 / 4000 - 7000 Kelvin |
| Colour rendering index Ra | Ra>90 (900 series)/ 80<Ra<90 (800 series) / Ra<80 |
| Lifetime | Standard (up to 14000h) / very long (up to 20000h) |

Fig. 9.12 Examples of metal halide lamps used mainly in indoor lighting.

Fig. 9.13 Examples of metal halide lamps used mainly in outdoor lighting. First three: for road and industrial lighting. Last four: for sports floodlighting.

14 Immediate re-ignition is only possible by applying a very high voltage pulse (typically 60 kV). For this purpose special, hot-restrike, lamps are produced with special heavily-insulated electrical contacts for applying this high voltage pulse.

# 10 High-pressure sodium lamps

High-pressure sodium gas discharge lamps belong to the group of HID lamps. The Philips designation for high-pressure sodium lamps is SON, where "SO" stands for sodium. High-pressure sodium lamps are also referred to as HPS lamps.

SON lamps, in common with all high-pressure discharge lamps, are relatively compact. By increasing the vapour pressure in a sodium lamp, the spectrum around the typical yellow sodium line broadens. The result is that colour rendering improves and the colour appearance changes from yellow to yellow-white (sometimes, in commercial literature, called golden white), albeit at the cost of a decrease in efficacy. However, the resulting efficacy is more than double that of a high-pressure mercury lamp. At its introduction in the late 1960's, a very efficient alternative was thus obtained for the many high-pressure mercury lamps employed at that time in road lighting. Today, road-lighting installations all over the world very often use high-pressure sodium lamps, although for some installations LED solutions have become an alternative.

By further increasing the sodium pressure, the colour quality of the light improves to such an extent that we really can speak of white light. These so-called White SON lamps have a lower efficacy but sometimes offer an acceptable alternative to halogen and compact metal halide lamps for accent lighting. The Philips designation for White SON lamps is SDW.

## 10.1 Working principle

We have seen with low-pressure sodium lamps (Chapter 7) that at the low working pressure of that discharge, a single, monochromatic line of light at a wavelength of 589 nm is emitted. With increasing pressure, the radiation in the core of the discharge is absorbed by the cooler surrounding gas and re-emitted in the form of radiation not of the 589 nm line but with wavelengths slightly smaller and slightly larger than 589 nm. So, the 589 nm line gradually disappears (called self-absorption), while in the wavelength area to the left and right of that value, more and more light is emitted (broadening of the spectrum). The phenomenon of self-absorption and spectrum broadening is illustrated in Fig. 10.1, which shows examples of sodium lamps with different operating vapour pressures. The phenomenon is accompanied by a loss of efficacy. At the operating pressure of a normal high-pressure sodium (SON) lamp, the lamp has a yellow-white colour appearance (2000 K) and a moderate colour-rendering index (Ra) of approximately 25 at an efficacy, for the higher wattages, of some 140 lm/W. With further increase in operating pressure the same process continues, viz. widening of the spectrum at the cost of efficacy. With lamps that operate at a four-times-higher pressure (Philips designation SON Comfort) the colour rendering improves to "fairly good" ($R^a$ = 65) at an efficacy of around 90 lm/W. A version with an operating pressure ten-times-higher than that of the standard SON lamp is also produced: Philips designation SDW, popularly called White-SON. This version has an $R_a$ of 80 and radiates white light with a colour temperature of 2500 K at an efficacy of around 45 lm/W.

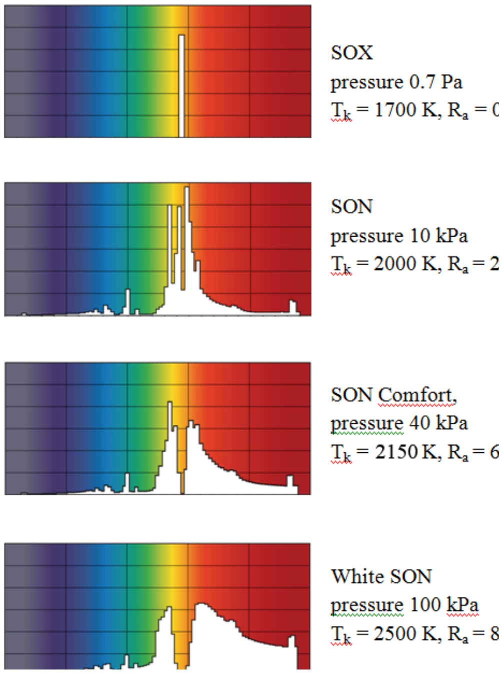



Fig. 10.1 Effect of sodium vapour pressure on the spectral power distribution of different sodium gas-discharge lamps.

## 10.2 Lamp construction

The main parts of a high-pressure sodium lamp are: (Fig. 10.2):

- discharge tube
- fill gas
- outer bulb
- electrodes
- lamp cap
- getter

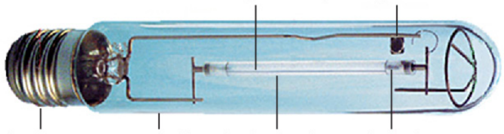



Fig. 10.2 Main parts of a high-pressure sodium lamp (example SON-T)

### 10.2.1 Discharge tube

We have seen in the Chapter on metal halide lamps that sodium (there from the sodium halide compound) at high temperatures has the tendency to migrate slowly through quartz (Section 9.2.1). We have also seen that ceramic discharge tubes withstand sodium at very high operating temperatures. This is why, right from their introduction in 1966 (long before metal-halide lamps started using ceramic material), high-pressure sodium lamps have translucent, tubular-shaped, ceramic discharge tubes.

### 10.2.2 Fill gas

The sodium is introduced into the gas discharge tube as a sodium-mercury amalgam composition, which partially vaporises when the lamp reaches its operating temperature. [15]

The sodium vapour is responsible for excitation and subsequent light radiation, while the mercury gas acts to regulate the voltage of the lamp and reduces thermal losses (buffer gas).

The starter gas normally added is xenon (an exception to this is found in the case of low-wattage SON lamps, which have a built-in igniter in the form of a bi-metal switch and a neon-argon mixture – the Penning mixture also used in fluorescent lamps – as starting gas).

It is known that by increasing the pressure of the starting gas xenon, the luminous efficacy of the lamp increases by about 20 per cent. However, to ensure proper ignition at this higher starting-gas pressure an auxiliary ignition wire has to be added very close to the discharge tube. Philips does this in a special series of high-efficacy lamps by integrating this auxiliary ignition wire, or strip (also called antenna), in the wall of the discharge tube (SON PIA, where PIA stands for Philips Internal Antenna - Fig. 10.3).

Fig. 10.3 Discharge tube without and with an internal ignition strip (or PIA).

From an environmental point of view it can be desirable to have high-pressure sodium lamps that do not contain mercury. Such lamps are, in fact, available. In these mercury-free high-pressure sodium lamps, xenon is used not only as a starting gas but also as the buffer gas that regulates the voltage and reduces thermal losses. Mercury-free high-pressure sodium lamps can be recognised by a green ring on the top of the outer bulb (as in Fig. 10.2).

### 10.2.3 Electrodes

The electrodes employed in high-pressure sodium lamps are basically the same as those found in high-pressure mercury lamps (Section 8.2.3).

### 10.2.4 Outer bulb

To thermally insulate the gas discharge tube and to protect its components from oxidation, an outer bulb is employed. The outer bulb of standard high-pressure sodium lamps is either tubular (SON-T) or ovoid in shape (SON) (Fig. 10.4). The internal wall of the ovoid bulb is usually coated with a diffusing powder.

Fig. 10.4 Coated ovoid (SON), Tubular (SON-T), and two White SON (SDW-T with different two-pin lamp caps).

The coated versions were introduced so as to obtain the same light-emitting area as in normal ovoid, fluorescent-powder-coated, high-pressure mercury lamps. In this way the coated ovoid high-pressure sodium lamps can be used with the same luminaire optics as those developed for high-pressure mercury lamps.

15 The final vapour pressure depends on the temperature of the coldest spot of the gas discharge tube, which in turn is dependent on the construction of the tube.

This was especially important at the original introduction of high-pressure sodium lamps, when they were replacing many existing high-pressure mercury lamps that were then being used in many road-lighting installations. Note that the coating in high-pressure sodium lamps is of the diffusing, non-fluorescent type. Since SON lamps produce practically no UV radiation, there is no point in using fluorescent powder.

White SON lamps (SDW) are usually only available in the tubular form. The glass used for the outer bulb for wattages of more than 100 W is hard glass.

### 10.2.5 Lamp caps

The lamp caps employed for normal high-pressure sodium lamps are of the Edison screw type. The white SON lamps (SDW) have a special bi-pin cap to ensure exact positioning in a luminaire (Fig. 10.4).

### 10.2.6 Getter

During the process in which the lamp is evacuated, it is impossible to remove all traces of air and water vapour. During the operation of the lamp minuscule particles evaporate from the glass and metals in the tube. All these traces would lead to an unacceptably short life. To remove them a getter is added that absorbs these traces. The getter is usually in the form of a small piece of solid material (see Fig. 10.2).

## 10.3 Performance characteristics

### 10.3.1 Energy balance

Fig. 10.5 shows the energy balance of a middle-range type of high-pressure sodium lamp. Some 30 per cent of the input power is emitted in the form of visible radiation. Compare this with the 40 per cent of low-pressure sodium lamps and the 17 per cent of high-pressure mercury lamps.

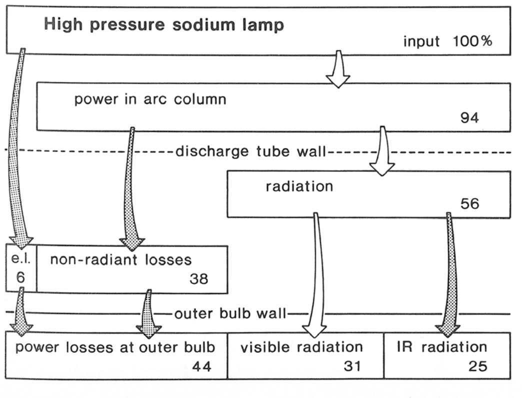



Fig. 10.5 Energy balance of a metal halide lamp (SON-T).

### 10.3.2 System luminous efficacy

The efficacy of the compact white SON varies between approximately 30 lm/W and 45 lm/W. The high-pressure sodium lamp with colour rendering index of 60 (SON Comfort) has an efficacy between 75 lm/W and 90 lm/W, and the normal high-pressure sodium lamps (SON with Ra around 25) an efficacy of between some 80 lm/W and 140 lm/W. Again, as always, the higher the wattage, the higher the efficacy.

### 10.3.3 Lumen-package range

Compact White SON lamps are available in lumen packages from some 1500 to 5 000 lumen (corresponding wattage range 35 W - 100 W). Normal high-pressure sodium lamps (SON) are being produced in the approximate range 4000 - 150 000 lumen (corresponding wattage range 50 W - 1000 W).

### 10.3.4 Colour characteristics

As with all gas discharge lamps, the high-pressure sodium lamp spectrum is discontinuous. Figs.10.6 - 10.8 show the spectra of a normal SON lamp, a SON Comfort lamp and a White SON lamp (SDW).

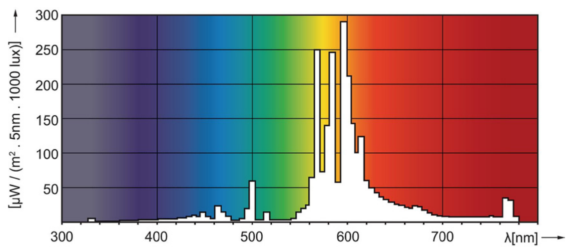



Fig. 10.6 Spectral energy distribution of a high-pressure sodium lamp (SON): Tk 2000 K and Ra 25.

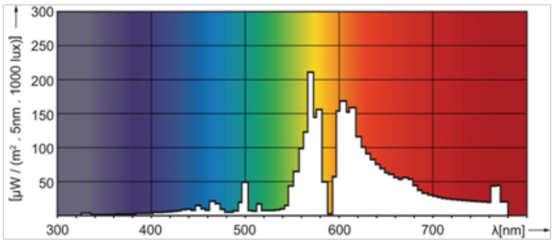



Fig. 10.7 Spectral energy distribution of a high-pressure sodium comfort lamp (SON Comfort): Tk 2150 K and Ra 65.

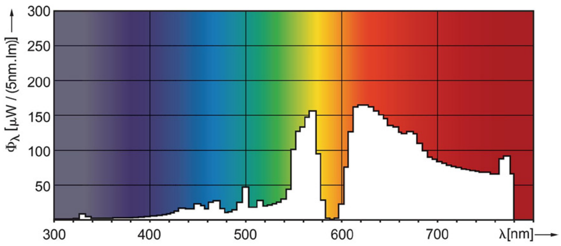



Fig. 10.8 Spectral energy distribution of a White high-pressure sodium lamp (SDW): Tk 2500 K and Ra 80.

The colour temperature of these versions ranges from 2000 K to 2500 K and the colour-rendering index from 25 to 80. Since the spectrum of all versions is relatively strong in the red wavelength area, the rendition of human faces is often experienced as being somewhat flattering. Of course, for indoor lighting the colour rendering of the normal high-pressure sodium lamp is far from adequate. For road lighting it is quite acceptable.

### 10.3.5 Lamp life

The lamp voltage of a high-pressure sodium lamp increases gradually with life.[16] The chief cause of lamp failure is that the lamp voltage rises higher than the voltage output of the ballast, causing the lamp to extinguish. When this happens, the lamp cools down and the pressure in the lamp decreases so that the igniter can ignite the lamp again. After some minutes, the lamp voltage again increases too much and the lamp extinguishes again. So, the normal end of life of a high-pressure sodium lamp is accompanied by this so-called cycling effect.[17] Normal high-pressure sodium lamps have an economic life of up to some 20 000 hours (20 per cent mortality).

The lifetime of White SON lamps is not determined by the moment of actual failure of the lamps but by the onset of too large a colour shift of the light, which is caused by the gradual increase of lamp voltage. To greatly increase their lifetime, white SON lamps therefore employ an electronic voltage stabiliser integrated into their control gear. The economic lifetime of compact White SON lamps, depending on type, lies between some 8000 and 12 000 hours (based on a 20 per cent too-large colour shift).

### 10.3.6 Lamp price

White SON lamps are a factor 25 to 40 times more expensive than GLS lamps. Normal high-pressure sodium lamps are some 8 to 60 times more expensive, depending on colour quality and wattage.

### 10.3.7 Lamp-lumen depreciation

For the compact White SON lamps, lumen-depreciation values vary between some 20 and 25 per cent (after 10 000 hours). The normal high-pressure sodium lamps have a much smaller lumen depreciation of between approximately 5 and 10 per cent (after 20 000 hours).

### 10.3.8 Run-up and re-ignition

The high-pressure sodium lamp must be ignited by a high-voltage pulse, typically 1.8 kV to 5 kV. After ignition, the colour of the light is initially white (discharge in the starting gas), changing to yellow after some twenty seconds as the sodium amalgam gradually vaporises and the vapour pressure rises, until after some 3 to 5 minutes, the nominal pressure and full light output is reached. Re-ignition of the hot lamp requires the lamp to cool down for about one minute to allow the pressure to decrease to a point where the ignition pulse can again ionise the sodium atoms.

### 10.3.9 Dimming

All high-pressure sodium lamps can be dimmed to a certain extent, depending on the type of dimming equipment used.

Lower wattages (100 to 150 watt) can be dimmed with special electronic gear, which allows for dimming to 20 per cent. Higher lamp wattages can be dimmed by including an extra inductive coil (ballast) in the ballast circuit. Lamp colour remains virtually constant and lifetime is not affected.

### 10.3.10 Ambient-temperature sensitivity

The behaviour of high-pressure sodium lamps during temperature variations differs from that of other discharge lamps because of the excess of amalgam used in the lamp. Although the outer bulb offers some

16 Mainly because of loss of sodium by combination of sodium with scattered emitter and tube-wall material.

17 For those situations where this on-off cycling might be disturbing or would damage the ballast, special "self-stopping" igniters are available that stops igniting the lamp once the high voltage at end of life is reached.

degree of thermal isolation, the lamp-manufacturer's specifications should be followed in the design of luminaires as far as its effect on lamp temperature is concerned.

### 10.3.11 Mains-voltage variation

A 5 per cent mains-voltage variation has a 15 per cent effect on the light output of high-pressure sodium lamps. The same 5 per cent mains-voltage variation has a 5 per cent effect on lamp voltage.

## 10.4 Product range

We have seen that high-pressure sodium lamps are available in three basic types: standard high-pressure sodium (SON), an improved-colour version of high-pressure sodium (SON Comfort), and a compact, white-light, high-pressure sodium lamp (SDW). We have also seen that the standard high-pressure sodium lamp is available in two forms: the standard one and an extra-high-efficacy version (SON PIA).

Most high-pressure sodium lamps contain a very small quantity of mercury, but there is also a version that is completely-free of mercury.

For ease of replacement of high-pressure mercury lamps in existing installations with more- efficient high-pressure sodium types, a special type of high-pressure sodium lamp has been developed. This type (Philips designation: SON-H) uses a neon-argon (Penning) mixture as starting gas, and is fitted with an ignition coil surrounding the discharge tube. These features allow the lamp to be operated on a standard high-pressure mercury-lamp ballast.

# 11 LEDs

LEDs are solid-state radiators where the light is created inside solid-state material. Light emission can be obtained when an electric current passes through specific types of semiconductor material. Common semiconductor diode chips, used today in so many electrical circuits, all use much the same technology. The light-radiating diode versions are called Light-Emitting Diodes, or LEDs. Because of their character they are sometimes also referred to as “opto-electronic” devices. Until the mid-nineties of the last century, LEDs had a low lumen output and low efficiency, making them only suitable as small indicator lamps (for example, in electrical appliances). Today, the efficacy of LEDs is comparable to that of gas discharge lamps. The lumen output of a single LED can be more than that of a 75 watt incandescent lamp. To distinguish these LEDS from the indicator type of LEDs they are referred to as high-brightness or high-power LEDs. We will concentrate in this course book on these types of LEDs.

Further improvements in high-brightness LEDs are expected, ultimately leading to efficacies of probably slightly more than 200 lm/W (for white-light LEDs). This is approximately twice the efficacy of today’s most efficient white-light gas discharge lamps. With its light-emitting surface of some 0.5 mm2 to 5 mm2, an individual LED chip represents the smallest artificial light source currently available. LEDs have a long lifetime and are, given the solid-state material, extremely sturdy. They are available in white and in coloured-light versions. The coloured versions, in multi-LED format, are extensively used in traffic signs. Coloured versions were also the first ones to be used on a large scale for lighting: specifically, the exterior floodlighting of buildings and monuments. Both the efficacy and the colour quality of white LEDs have been improved so much that they are now used in many different lighting applications, including road lighting, indoor accent lighting, domestic lighting and automobile lighting. Examples of the use of LEDs for office lighting and outdoor sports lighting can also be found. Given the potential for a further increase in their efficacy, the number of LED applications is bound to increase. Their small size and their availability in many different colours, and the simplicity of lighting control, both in terms of dimming and colour changing, are properties that permit of completely new applications.

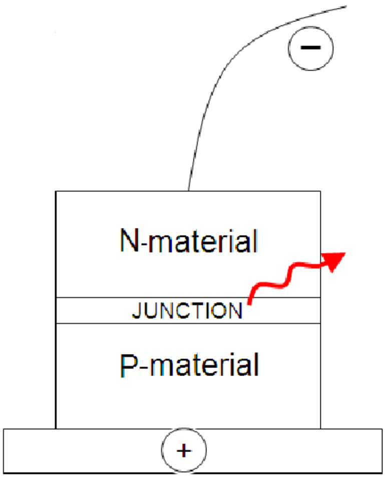
Fig 11.1 Different LED applications: indicator lamp, traffic sign, LED line for architectural lighting, road-lighting luminaire, LED spot (white and dynamically-coloured light), LED bulb and car rear light.

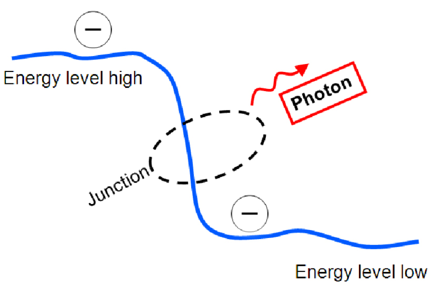
## 11.1 Working principle

### 11.1.1 Principle of solid-state radiation

Like any diode, a LED consists of layers of p-type and n-type of semiconductor material.

The n-type of material has an excess of negatively-charged electrons whereas the p-type material has a deficiency of electrons, viz. positively-charged holes. Applying a voltage across the p-n semiconductor layer pushes the n and p-type atoms towards the junction of the two materials (Fig. 11.2). Here the n-type of atoms "donate" their excess electrons to a p-type of atom that is deficient in electrons. This process is called recombination. In doing so, the electrons move from a high level of energy to a lower one, the energy difference being emitted as light. The wavelength of the light is dependent on the energy-level difference between the p and n materials, which in turn is depends on the semiconductor material used: different semiconductor materials emit different wavelengths, and thus different colours, of light. The spectrum is always a narrow-band spectrum (quasi-monochromatic light).



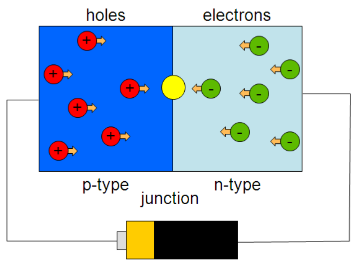




Fig. 11.2 Principle of operation of solid-state radiators.

> Semiconductors are made of material that is a poor conductor of electricity. By adding specific impurities to the material, a process called doping, the atoms of the material get either extra electrons or a deficiency of electrons. This doping process makes the material more conductive, which is the reason for the name semi-conductor. The material with extra electrons is an n-type of semiconductor (negatively charged) and the material with a deficiency of electrons viz. positively-charged "holes", is a p-type of semiconductor. In the n-type of material the extra electron of an atom moves in an outer orbit with a correspondingly-higher energy level. In the p-type of material the missing electron of an atom was moving in a lower orbit with lower energy level. After applying a voltage across the p-n junction, an n-atom can meet a p-atom at the junction and the electron of the n-atom falls into the lower orbit of the p-atom with the correspondingly-lower energy level. The energy difference may be radiated as radiation (flow of photons) or may heat up the material. Semiconductor material is chosen with a value of the energy difference that results in radiation in the visible range (according to E = h . c / λ; (see Section 1.2 of the Course book "Basics of Light and Lighting). The process is very much like the process of excited electrons in a gas discharge falling back to their original orbit with a lower energy level while emitting light. In this sense it is surprising that the expression "solid state discharge" and "solid state discharge lamp" is hardly ever used.

Not all recombinations result in light emission. Some recombinations are non-radiative and just heat up the solid material. This limits the efficiency of light creation. A further limitation of the efficiency is caused by absorption of light in the solid material of the chip itself. Improvements in radiative-recombination efficiency and light-extraction efficiency have been the most important reasons for the dramatic improvements of efficacy of LEDS during the past decade. Further improvements will be sure to greatly increase the efficacy of LEDs over the coming decade.

### 11.1.2 Principle of White LEDs

The spectrum of a single LED is always narrow. Consequently, its light is coloured. White LED light can nevertheless be obtained by combining three (or more) differently-coloured LED chips. A common method is to combine red, green and blue LED chips into a single module to produce white light (RGB LED, Fig. 11.3).

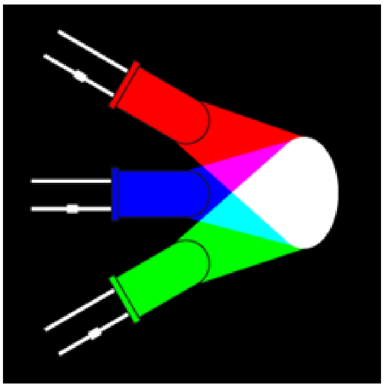
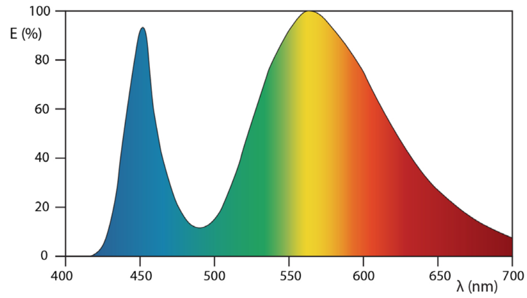


Fig. 11.3. White light by combining red, green and blue LED light.

However, the colour rendering of such a "RGB white light" system is not good, since large areas of the full colour spectrum are not included in its light. Sometimes an amber colour chip is added to the RGB combination to improve the colour quality of the light (RGBA LED).

Research is going on to produce single, multi-layer LED chips, each layer producing a specific colour of light. A single LED producing red, green and blue light would therefore result in white light.

Good-quality white light, which is especially important when it comes to providing good colour rendering, is obtained by using a blue LED chip in combination with fluorescent material that converts much of the blue light into light of different wavelengths spread over almost the whole visible spectrum (Fig. 11.4). The working principle of fluorescent powders converting UV radiation into visible radiation (as explained in Section 4.2.4 of the Chapter on fluorescent lamps) is the same for powders converting blue light into visible radiation of longer wavelengths. In LED technology it is customary to call such fluorescent materials, phosphors: hence white LEDs based on this principle are called "white-phosphor LEDs". By mixing different phosphors in different proportions, white LEDs producing different tints of white light with different colour-rendering capabilities can be made.



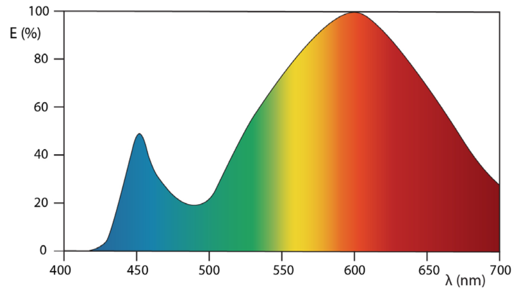




Fig. 11.4 The relative spectral power distribution of a typical white-phosphor LED.

Top: colour temperature Tk = 4000K, colour rendering Ra =70

Bottom: colour temperature Tk = 2750K, colour rendering Ra = 85.

## 11.2 LED construction

The LED chip is embedded in a larger structure for mechanical protection, for the electrical connections, for thermal management, and for efficient light out-coupling. The main parts of a LED are (Fig. 11.5):

- semiconductor LED chip
- reflector cup
- supporting body
- electrodes and bond wires
- heat sink
- primary and secondary optics
- phosphors (for white LEDs)

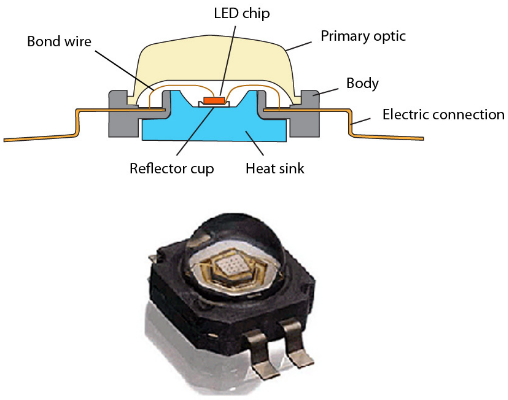



Fig. 11.5 The main components of a high-brightness LED.

### 11.2.1 Semiconductor chip material

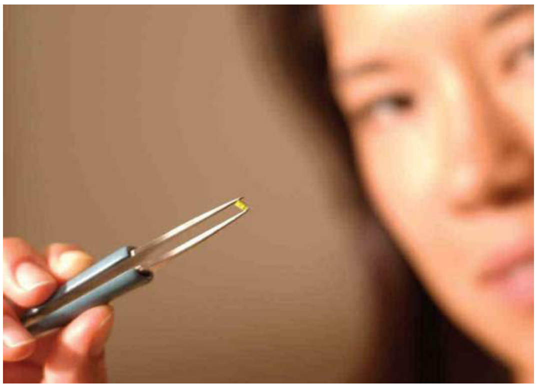


Fig. 11.6 Seen here held in tweezers: the LED chip, or die.

The p-n semiconductor sandwich forms the heart of the LED and is called the LED chip, or die (Fig. 11.6).

The semiconductor material used in an LED determines the difference in energy level between the n and p junction which, as explained above, in turn determines the wavelength and thus the colour of the light emitted. For LEDs, compound semiconductor material is used, which is composed of different crystalline solids. These are doped with very small quantities of other elements (impurities) to give their typical n and p properties. Materials used in semiconductors for high-brightness LEDs must also be able to handle the necessary electrical currents, heat and humidity, and must have a high degree of translucency (which is, in fact, the case with crystalline solids). The elements aluminium, indium, gallium and phosphide (ALInGaP) are used, in different compositions, to produce the colours amber, orange and red in high-brightness LEDS (Fig. 11.7). For the colours blue, green and cyan the elements indium, gallium and nitride (InGaN) are used (see again Fig. 11.7). It was the Japanese Nakamura who, in 1993, succeeded for the first time in producing a blue LED suitable for mass production. This was the "missing link" that enabled the production of white-phosphor LEDs and the production of white LED light on the basis of mixing the light of red, green and blue LEDS (RGB mixing). Since then, the development of high-brightness LEDs for lighting has taken off very rapidly. As can be seen from Figure 11.7, today a very small area of the spectrum, in greenish-yellow, is still missing.


Fig. 11.7 The main semiconductor material elements used in high-brightness LEDs, with examples of the corresponding light colours.

#### Shape

Unfortunately, the LED chip is a "photon or light trap": that is to say, much of the light emitted within the chip is internally reflected by its surfaces (borders between the material and air) and ultimately, after multi reflections, absorbed in the material (heating up the material). Only light that hits the outer surface more or less perpendicularly (± approximately 20 degrees) can leave the material (Fig. 11.8). By giving the chip a specific shape and by keeping it thin, the so-called light-extraction efficiency can be improved. Fig. 11.9 gives an example of such a specifically-shaped chip.

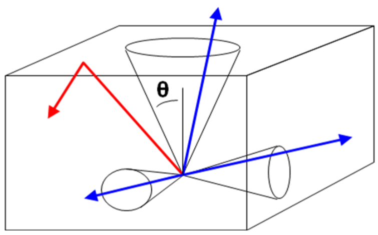



Fig. 11.8 Light-escape cones at the border of solid material and air. Angle θ is approximately 20 degrees.

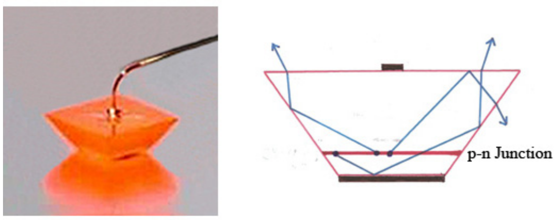



Fig. 11.9 An example of a specifically-shaped LED chip that improves light-extraction efficiency. On top of the chip, the anode with its bond wire can be seen.

18 It is the basic semiconductor materials and not the dopes that determine the wavelength of the radiation.

### 11.2.2 Reflector cup

In many cases, the chip is placed in a reflector cup which, because of its shape, helps to direct the light in an upwards direction. Highly-reflective material is used: for example, metal or ceramic material. The reflector cup can be considered to be part of the primary optics of the primary optics of the LED (see next Section).

### 11.2.3 Primary and secondary optics

The silicon lens on top of the LED chip serves as protection for the chip. More importantly, it helps in increasing the light extraction from the chip and as such is essential for a high lumen efficacy of the LED.[18] The lens itself does not shape the beam. The material of the lens and of the reflector cup should be such that degradation (for example lens yellowing) is minimised in order to minimise lumen depreciation over life.

Secondary optics to accurately shape the light beam for different applications can be separately incorporated in the LED luminaire or fitted direct to the LED housing. Fig. 11.10 shows a number of different secondary optics fitted direct to the LED housing.


Fig. 11.10 Examples of secondary optics fitted direct to the LED housing

### 11.2.4 Electrodes and bond wires

In order to be able to apply power to the chip, the p and n parts of the chip have metal contacts called electrodes (the cathode is connected to the n-part of the chip and the anode to the p part). Bond wires connect the electrodes with the electrical connections. They are usually gold wires. Fig. 11.9 shows such an electrode (anode) with a bond wire. Since the electrodes intercept light leaving the chip, the dimensioning of the electrodes and bond wires, especially on the side of the main light-escape route, is one of the factors that determines the light efficiency of the LED.

### 11.2.5 Heat sink

LEDs do not radiate infrared radiation and consequently give a cool beam of light. However, this does not mean that they do not generate heat. Non-radiative recombinations of electrons and holes in the p-n sandwich, and light trapped in the chip, do heat up the chip. The larger the power of the chip and the lower its luminous efficacy, the higher is this heating effect. The higher the temperature of the p-n junction in the chip, the lower the light output of the chip. A too-high chip temperature also seriously shortens LED life, and it also slightly shifts the emitted wavelength and thus the colour of the LED. Effective thermal management is therefore critical for a proper functioning of LEDs. All high-power high-brightness LEDs therefore have a heat sink of high-thermal-conductivity material (like aluminium or copper) on their rear side to conduct the heat away from the chip and through the luminaire housing to the surrounding air. LED luminaires must therefore incorporate in their design thermal conduction and convection features (such as cooling fins Fig 11.11) to dissipate the heat to the immediate surroundings.

Fig. 11.11 Examples of luminaires with cooling fins.

For retrofit LED lamps (LED bulbs), the size of the heat sink is limited by the size of the bulb. The heat sink therefore has a limited capacity, thus limiting the power of the retrofit LED bulbs employed (with today's LED efficacies, to something like 75 watt incandescent-lamp equivalent). If active cooling is employed, larger powers are permissible.

### 11.2.6 Phosphors

As mentioned above, the most important method for producing white light with LEDs is by applying a phosphor coating to a blue-light LED that converts part of the blue light into longer-wavelength green, yellow and red light. Different compositions of different phosphors are used to produce white light of different colour tints. Since the basis of the process is the blue light of the chip, the final efficacy will become higher as more blue is kept in the light. However, this implies a high colour temperature (cool-white light) and relatively-poor colour rendering. If, with a different phosphor composition, more blue light is converted, the colour quality will improve at the expense of a somewhat-lower efficacy. We see here the same balancing effect between colour quality and lamp efficacy that we have seen with conventional

18 By introducing a lens medium between the chip and the air with a refractive index value between that of air and that of the chip material, the angle over which light can escape from the chip increases (angle $\theta$ of figure 11.8). By shaping the outer surface of the lens, almost all the light that escaped into the lens material can escape from it into the air without further losses.

lamps. For more information on phosphors see Section 4.2.4 “Fluorescent powder”of Chapter 4 ”Tubular Fluorescent lamps”.

**Phosphors applied direct to the chip**

The phosphor is often applied on or very near to the blue LED chip (Fig. 11.12)

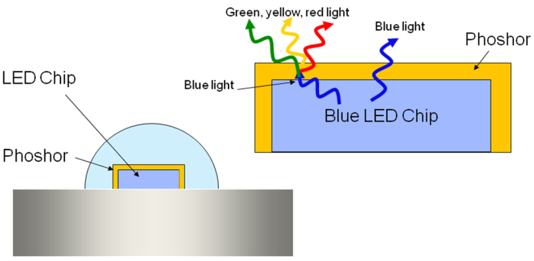



Fig. 11.12 Principle of creating white light with a blue-light chip covered with phosphor.

The phosphor is often mixed with a solvent and then poured over the chip. This is called a non-conformal coating process. It results in a variation of the thickness of the phosphor layer. This thickness variation causes a variation of the colour temperature in the light beam as shown in Fig.11.13 left. Philips Lumileds employ a unique process for coating the chip with a conformal phosphor layer. The resultant advantage of employing this process (Fig.11.13 right) is that there no colour variation in the light beam.

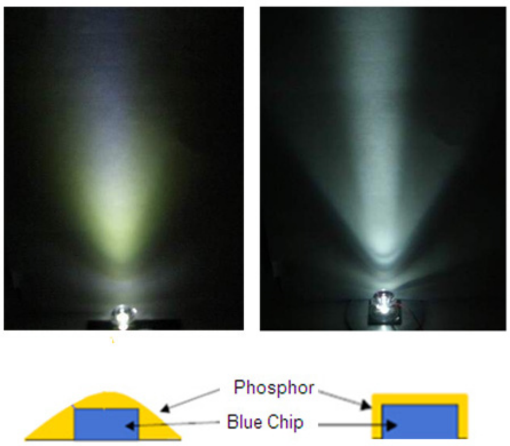



Fig. 11.13 On the left: light beam obtained with non-conformal phosphor coating, and on the right: light beam obtained with conformal coating.

**Remote-phosphor LED modules**

In the case of multi-LED units, the phosphor is sometimes applied at a greater distance from the LEDs. Such modules are called remote-phosphor LED modules (Fig. 11.14). Here, a number of blue LEDs are placed inside a mixing chamber of high and diffuse reflective material. The phosphor layer, positioned remotely from the LEDs on the bottom of the chamber, converts the blue light of the chips into white light. In this way, thanks to the mixing process, small differences in light output and or colour of individual chips are not visible. The risk for disturbing glare is also reduced because the light intensity from the large-sized phosphor layer is much lower than the intensities of small, individual LEDs. Some types of retrofit Philips LED bulbs apply a similar remote phosphor technology (Fig. 11.15)

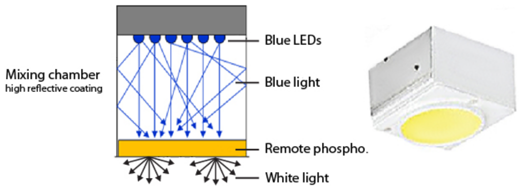



Fig. 11.14 Principle of a remote-phosphor LED module creating white light.

Fig. 11.15 Philips LED bulb producing high-quality white light with remote phosphor. Left: parts of the LED bulb, from bottom to top: lamp cap, electronic driver, heat sinks, two arrays with six LEDs, secondary optics, remote phosphor, top seal.

The phosphors used for the blue-light conversion appear yellow when they are not activated; that is to say, when the LED is not switched on (see photographs of Figs 11.14 and 11.15). This sometimes makes people think, erroneously, that the blue light is filtered through a yellow filter. It is really wavelength conversion and not light filtering that takes place.

### 11.2.7 Multiple LED modules

Fig 11.16 LED module with multiple LEDs mounted on a printed-circuit board.

The luminous flux of one individual LED is quite low compared to that of conventional light sources. Multiple LEDs are therefore often packed on a printed-circuit board (PCB) to obtain an LED module emitting a high luminous flux. The PCB establishes the electrical connections between all components and the external electrical driver. The PCB must also conduct the heat from the heat sinks of the LEDs to the outside world. PCBs can be of glass-fibre reinforced epoxy material, ceramic material or metal-core material (aluminium, with a thin layer of fibreglass for electrical insulation).

Conventionally, the electrical connections are made by soldering and in that case we speak of Surface Mounted Devices, SMDs. Since high temperatures can damage the chips, SMD type of packaging requires an accurate process control. A more advanced way of packaging LEDs on PCB's is the so-called Chip On Board method, COB. Here the LED chips are directly, without a substrate layer, connected to the PCB with conductive glue. The electrical connections are directly made through the bond wires. No soldering is required, a higher packaging density is possible and thermal management can be optimized more easily. What packaging method is most suitable, also taking the economic aspect into account, is dependent on the type of application.

## 11.3 Performance characteristics

### 11.3.1 Temperature of the chip junction

It has already been mentioned that with rising temperature of the p-n chip junction, the performance of LEDs decreases: particularly the light output and lifetime. The performance data are usually specified for a junction temperature ($T_j$) of 25°C.[19] However, under normal operating conditions, a junction temperature of 60°C to 90°C is easily obtained. Depending on LED type, the lumen output falls to 60 to 90 per cent when the junction temperature increases from 25°C to 80°C. As the power dissipated by the LED remains the same, this affects both the luminous efficacy and the lumen output. Specification of performance data at a junction temperature of both 25°C and say 80°C would give a much better insight into what we may expect under real-life conditions. Amber and red LEDs are the most sensitive to changes in junction temperature, and blue LEDs the least.

### 11.3.2 Binning

The mass production of LEDs results in LEDs of the same type varying in colour, light output and voltage. In order to ensure that LEDs nevertheless conform to specification, LED manufacturers use a process called binning in their production process. At the end of the manufacturing process, LED properties are measured and LEDs are subsequently sorted into subclasses, or "bins" of defined properties. As far as the colour quality is concerned, the tolerances in these definitions are such that visible differences in colour between LEDs from the same bin are minimised. As the definition of a bin does not change with time, the same quality is also assured from production run to production run.[20]

With the advancement of knowledge concerning LED materials and the mass-production process, we may expect that binning will ultimately no longer be required. In fact Philips Lumileds has already introduced LED products onto the market of the highest-possible quality without using the binning process ("binning-free LEDs").

### 11.3.3 Energy balance

The energy balance of a LED is much easier to specify than that of conventional light sources. This is because no energy is radiated in the UV and infrared region of the spectrum, which means that the energy balance comprises only visible radiant energy and heat energy. Today, White LEDs transform 20 to 30 per cent of the input power into visible light and the remaining part (70 to 80 per cent) into heat.

The light percentage comes close to that of fluorescent lamps, and will soon supersede.

19 LED manufacturers measure the luminous flux of their LEDs using a 15-20 millisecond power pulse that is so short that it does not increase the junction temperature above the ambient temperature of 25°C of the laboratory.

20 The tolerances are based on so-called MacAdam ellipses that contain all colours that are for the eye indistinguishable.

### 11.3.4 System luminous efficacy

Sometimes, luminous efficacies are specified for the bare chip. It is evident that the ancillary devices described in the previous Sections, which are essential for a proper functioning of LEDs, absorb light. The only realistic thing to do, therefore, is to specify luminous efficacy (and light output as well) for the total LED package. As with most conventional lamps, the luminous efficacy of LEDs is dependent on the power of the LED and on the colour quality of the light it produces. Higher-power LEDs have higher efficacies, while those with better colour rendering have lower efficacies. Today (end of 2011), cool-white LEDs are commercially available in efficacies up to slightly more than 100 lm/W, and warm-white LEDs with colour-rendering indices larger than 80 in efficacies of around 80 lm/W (all lm/W values include driver losses). These figures do not take into account losses in secondary optics.

Retrofit LED bulbs with warm-white light (around 2700 K) and colour-rendering index better than 80 are available in efficacies up to 70 lm/W. Here, too, cooler-white versions are slightly more efficient.

As discussed at the beginning of this Chapter, in coming years we may expect to see further important improvements in luminous efficacies for white LEDs – even up to slightly more than 200 lm/W.

### 11.3.5 Lumen-package range

Today, single LEDs exist in lumen packages varying from a few lumens (indicator lamps) to some 1000 lumens. In the latter case, severe screening is called for to restrict glare, because so much light comes from such a very small light-emitting surface. By mounting multi LEDs on a printed circuit board, LED modules can be achieved with much larger lumen packages.

### 11.3.6 Colour characteristics

Principally, LEDs have a quasi-monochromatic, narrow-band spectrum. Figure 11.17 shows the spectra of blue, green and red LEDs.[21]

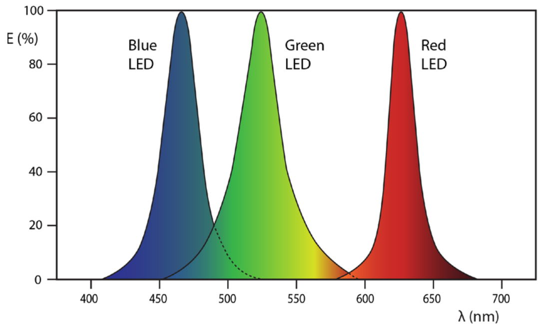



Fig. 11.17 The relative spectral power distributions of typical blue, green and red LEDs.

21 The half-maximum width of the spectrum bands is smaller than ca.50 nm.

Earlier, we discussed what colours could be produced by using different semi-conductor materials. Fig. 11.7 visualised these colours: all the colours of the spectrum can be made with the exception of a small gap in the green-yellowish region. We also saw that white light can be produced by mixing different colours: as, for example, as is done in RGB lighting. With some LED modules that make use of RGB mixing, the different coloured LEDs can be controlled (dimmed) individually. With such LED modules the colour of the light can be dynamically changed from white to all colours of the spectrum. changed from white to all colours of the spectrum.

It has also already been explained that white light of moderate-to-excellent colour rendering can be obtained by phosphor LEDs. They can have a near-continuous spectrum as shown already in Fig. 11.4). By applying different phosphors, white light within the colour temperature range of 2700 K to 10 000 K can be produced. Often, the higher-colour-temperature versions have only moderate colour rendering (Ra between 50 and 75). In the lower-colour-temperature versions, LEDs are available with good (Ra larger than 80) to excellent colour rendering (Ra larger than 90 or even 95). As with all lamps, better colour quality comes at the cost of lower efficacy.

White LEDs, like some fluorescent lamps, have one or more narrow peaks in their spectrum. The general colour rendering index Ra does not always give a good enough representation of the colour rendering capability of these light sources. CIE is therefore investigating new methods for assessing the colour rendering properties of white light sources with the goal of recommending a new colour-rendering metric.

### 11.3.7 Beam control

For lighting designers, one of the most interesting properties of a LED is its small light-emitting surface. This allows the creation of very accurately defined beams. As an illustration of this, Fig. 11.18 shows a near-parallel light beam made with a LED-line luminaire that is impossible to create with conventional light sources. Conversely small light-emitting surfaces often need properly designed and engineered screening in order to limit excessive glare.

Multi-LED luminaires have also multi light beams that may cause multiple shadows because a lighted object is illuminated from many slightly-different directions. With RGB colour mixing, this may lead to disturbing, multi-coloured shadows. How well the individual beams overlap and mix is for some applications an important quality criterion.

Fig. 11.18 Near-parallel light beam with a LED-line luminaire.

### 11.3.8 LED life

In the case of high-performance LEDs it takes a very long time before they actually fail – usually considerably more than 50 000 hours. Before that time, however, their lumen depreciation is so great that the LED is no longer giving sufficient light for most applications. Therefore, for LED lifetime specifications, the length of time that it takes to reach a certain percentage of its initial light value is used. Based on a depreciation value of 70 per cent, lifetime values of between 35 000 and 50 000 hours are common for high-performance LEDs. LED-bulbs, with their limited space for handling heat, have a lifetime of some 25 000 to 35 000 hours (25 to 35 times longer than an incandescent lamp). The temperature of the chip's junction has an influence on both the number of actual LED failures and the precise point in time when the 70 per cent lumen- maintenance point is reached.

### 11.3.9 LED price

Today, LED products are usually more expensive than the conventional light sources they replace. The higher investment cost, however, is for many applications more than balanced by the lower energy costs and, because of the long life of LEDs, because of the lower lamp-replacement costs. Expectations are that the coming ten years will see a halving of LED prices over each three-year period.

### 11.3.10 LED-lumen depreciation

The electric current passing through the chip's junction, and the heat generated in it, degrade the chip material and is so responsible for light depreciation. Decolouration of the housing and yellowing of the primary lens may be further reasons for lumen depreciation. In white phosphor LEDs, chemical degradation of the phosphor material also causes lumen depreciation. As mentioned already in the Section on LED lifetime (11.3.8), for high-performance LEDs 30 per cent lumen depreciation is reached at around 35 000 to 50 000 hours. Lumen-depreciation values are very much dependent on what temperature the chip's junction reaches in its application.

### 11.3.11 Run-up and re-ignition

LEDs give their full light output immediately after switch-on and after re-ignition.

### 11.3.12 Dimming

LEDs can be dimmed by simple pulse-width modulation down to five per cent of full light output (see Chapter 14). Not all retrofit LED lamps can be dimmed on normal, commercially-available dimmers. Special retrofit LED lamps that are designed to be dimmed on such dimmers are so specified on their packaging.

### 11.3.13 Ambient-temperature sensitivity

As has already been mentioned, limitation of the junction temperature of the LED chip is essential for the proper functioning of LEDs in terms of lumen output, lumen efficacy, lamp life, and even colour properties. In high-temperature environments the products perform worse, while at low temperature they perform better. The actual influence of the junction temperature is different for the different types of LEDs. In extreme temperature environments, therefore, relevant information for a particular product has to be obtained from the manufacturer.

### 11.3.14 Mains-voltage variations

As will been explained in Chapter 14, LED drivers are designed to drive LEDS on constant current. In this way the influence of mains-voltage variations is not an issue.

### 11.3.15 UV and IR component

LEDs radiate only visible radiation. There is no ultraviolet or infrared radiation.[22]

## 11.4 Product range

LED products are available as:

- single LEDs (Fig. 11.19)
- multiple LEDs on flat or three-dimensional PCB boards (Fig 11.20)
- LED modules (or LED engines) with secondary

22 Principally, it is possible to produce white-phosphor LEDs on the basis of a UV LED instead of a blue-light LED. But these would have a short life and are not normally commercially available.

optics and with or without built-in driver that can be used in the same way as lamps. Interfaces are standardised for interchangeability (Fig. 11.21)
- multiple LEDs on strings (Fig. 11.22)
- retrofit LED lamps with built-in driver (Fig. 11.23)

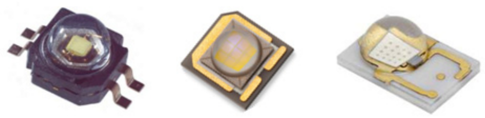


Fig. 11.19 Single LEDs.

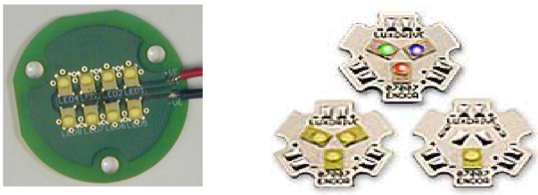


Fig. 11.20 PCB-mounted LEDs.

Fig. 11.21 LED engines (bottom: for use in road lighting) .

Fig. 11.22 Foldable LED string.

Fig. 11.23 Retrofit LED lamps for incandescent, halogen and fluorescent lamps respectively.

For users it can be important that LED modules (also called LED engines), like most conventional lamps, are interchangeable with products from different manufacturers. Zhaga, a global industry-wide cooperation, produces standard specifications for the interfaces of LED engines. The specified interfaces are not dependent on the LED technology used in the LED engine, because the LED engine is treated as a "black box". LED-engine manufacturers can therefore develop and innovate their product completely independently. Luminaire manufacturers that make use of such engines can also develop and innovate independently, because the luminaire is also treated as a black box. Interchangeability is achieved by defining interfaces for the physical dimensions, and for the thermal, electrical and photometric (beam) properties of the LED engine.

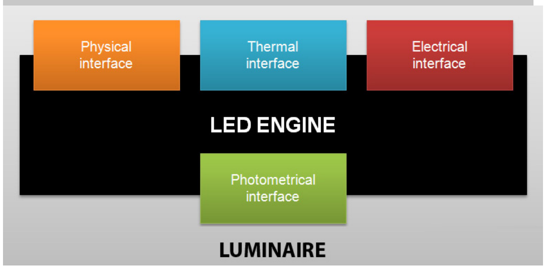



Fig. 11.24 LED engine and luminaire are treated as black boxes in the Zhaga specification of LED-engine interfaces.

# 12 OLEDs

Fig. 12.1 Flat OLED light sources.

OLEDs are flat, solid-state light sources built up of organic semiconductor layers. In contrast to the high-brightness, quasi-point-source LED, an OLED is a planar light source of low to medium brightness (Fig. 12.1). The name OLED stands for Organic Light Emitting Diode.[23] Serious development of OLEDs only started in the mid-nineties of the last century. OLEDs can be produced to give most colours of the spectrum, and white. The technology permits the production of OLED-windows that are transparent when not switched on (Fig.12.2).

OLED lighting products are now gradually coming onto the market in sizes up to some 30 cm x 30 cm with moderate efficacy and lifetime. The expectation is that the size, the efficacy, and the lifetime will rapidly improve. Initially, the most interesting application for OLEDs is architectural and decorative lighting. For general lighting purposes the efficacies have to be improved much further. Ultimately, white-light, large-sized OLEDs with efficacies up to 150 lm/W would seem to be possible.

Fig. 12.2 OLED window.

## 12.1 Working principle

The process that is responsible for the emission of light in OLEDs is very similar to that with LEDs: positively-charged holes and negatively-charged electrons are pushed through semiconductor layers towards each other and recombine. Part of these recombinations results in the emission of light. The colour of the light is dependent on the composition of the semiconductor material. White light can be obtained by bringing phosphorescent material in the emissive layers.

## 12.2 Construction

The organic layers are placed between electrodes, the one on the light-extraction side being transparent (Fig. 12.3). The layers are supported by a glass substrate and, for protection of the organic materials against oxygen and water, are sealed in glass.

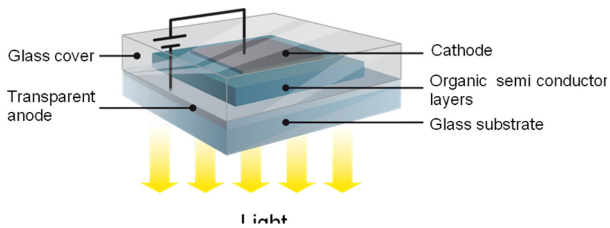



Fig. 12.3 Composition of an OLED.

Development is going on to substitute the glass seal by thin-film encapsulation. This development not only reduces the thickness of OLEDs but also opens up the possibility of bendable OLEDs. The first laboratory examples have already been produced.

23 Organic material is a semiconductor chemical compound whose molecules contain carbon and hydrogen (C - H bonds).

# 13 Electrical control gear for gas discharge lamps

Gas discharge (and solid-state) lamps cannot function properly when they are operated directly from the mains supply voltage. Certain electrical and/ or electronic peripherals have to be built into the lamp circuit, either in the lamp itself or externally. The collective name for these devices is electrical control gear. The control gear performs a number of functions: it ensures that the lamp can be started and, once started, can be operated stably over a longer period and, if the lamp type enables it, can be dimmed. All this should be done so that operating the lamp has no negative effects on the electricity network. The devices needed are called igniters, ballasts and dimmers. The type and quality of electrical control gear used determines the energy efficiency with which lamps are operated.

## 13.1 Igniters

### 13.1.1 Basics

Incandescent, halogen and solid-state light sources start immediately after connecting them to the proper power source. Most of the gas discharge lamps have such a high internal resistance that they need a voltage peak, higher than the normal operating voltage, to initiate the discharge. Such an igniter device is sometimes also referred to as a starter, especially in the case of fluorescent lamps. The igniter is so designed that after the lamp is ignited the high voltage pulses stop.

### 13.1.2 Starters for fluorescent lamps

In most fluorescent lamp circuits (including those of compact fluorescent lamps), the electrodes are preheated for a few seconds before a high voltage peak is applied across the lamp to initiate the discharge. Preheating oof the electrodes facilitates the emission of electrons. In non-electronic systems, glow-switch starters are used for this purpose (Fig. 13.1). The operating principle is illustrated in Fig. 13. 2..

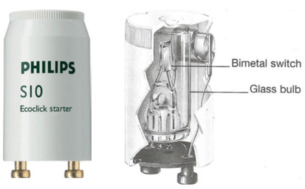



Fig. 1 3.1 Glow-switch starter.

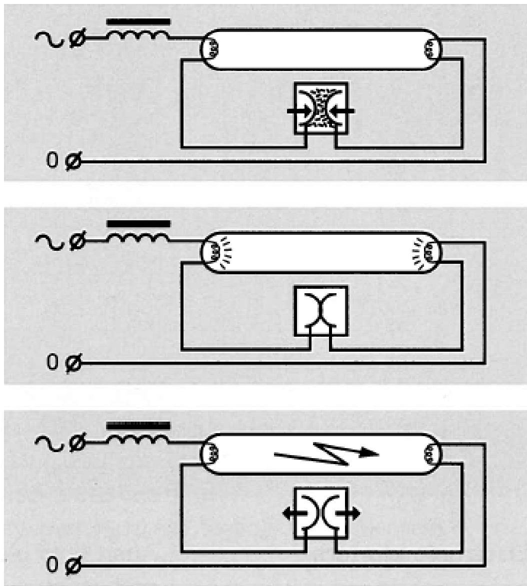


Fig. 13.2 Principle of a glow-switch starter. Top: The bimetal switch is open and because of the voltage applied a gas discharge is initiated across it. Middle: the gas discharge across the switch has heated the metals so that they bend together and close. The current then flows through the lamp electrodes, heating them. Under: the switch cools down and upon opening causes a voltage peak across the preheated lamp electrodes, initiating the gas discharge between them.

When a voltage is applied to the cold lamp, with the glow-switch starter open, a (glow) gas discharge is initiated between its bimetal contacts. The heat from the glow discharge causes the bimetal contacts to bend until they make contact, causing a current to start flowing through the lamp electrodes, so heating them. The switch then cools down, and upon opening again after a short while the current is suddenly interrupted causing a voltage peak across the preheated lamp electrodes in the order of 1000 V, which is sufficient to ignite the lamp. If the lamp does not ignite the first time, the process is automatically repeated, which causes flickering during the short ignition period.

The glow-switch starter is the traditional technology, known for its low initial cost. However, its harsh peak voltages have a negative effect on lamp life. Electronic starters with exactly the same functions as the glow-switch starter, but with a better-controlled voltage peak, are available as direct replacements (Fig. 13.3). They always ignite after one ignition pulse, so eliminating flickering during ignition. Because of the better control of the ignition peak, electrodes suffer less damage so that lamp life increases. Electronic starters automatically switch off defective or end-of-life lamps to protect the starter and the control gear.


Fig. 13.3 Electronic starter as a direct replacement for the glow-switch starter.

Where the traditional igniter was a separate device in the electrical circuit, with a modern electronic lamp ballast (see next Sections) the ignition function is electronically incorporated in this ballast.

### 13.1.3 Igniters for HID lamps

Ignition of HID lamps is initiated by a high peak voltage without pre-heating of the lamp electrodes.

Only in exceptional cases are glow-switch starters employed for HID lamps. Some low-wattage high-pressure sodium lamps have an internal igniter, in the form of a glow-switch starter, built into their lamp base.[24]

High-pressure mercury lamps have an ignition voltage lower than the (230 V) mains voltage and therefore do not need an igniter.

The ignition voltage of most low-pressure sodium lamps is normally less than twice the (230 V) mains and can therefore be obtained with the aid of a transformer that increases the mains voltage sufficiently to ignite the lamp.[25] Low-pressure sodium lamps produced for use with electronic igniters (SOX-E and SOX-HF types) are more efficient.

Metal halide HID lamps need an ignition voltage peak of 600 to 5000 volts and high-wattage high-pressure sodium lamps some 3000 to 5000 volts. They are normally started using an electronic igniter that generates a series of high-voltage pulses of the required magnitude. The electronic circuit is so designed that these pulses cease after ignition has taken place. Fig. 13.4 shows an example of an electronic igniter for an HID lamp


Fig. 13.4 Electronic igniter for an HID lamp.

Because of differing requirements for ignition voltage, shape of voltage peak and number of voltage pulses within a certain period, each type of HID lamp (and often also each different wattage) needs its own type of igniter.

## 13.2 Ballasts

### 13.2.1 Basics

**Limitation and stabilization of lamp current**

Ballasts are devices that limit and stabilize the lamp current. The electrical mains supply of constant voltage can be considered as an unlimited source of electric current. If mains voltage is supplied to electrical devices, the current has to be limited otherwise it will keep increasing until the device or circuit in which it is flowing breaks down. In many electrical devices the internal electrical resistance of the device limits the current. These are devices with a so-called positive- resistance characteristic in which the current is automatically limited to a small range. The range values are determined by the variations in the mains voltage (Fig. 13.5). Incandescent lamps (including halogen lamps) have a positive-resistance characteristic and thus need no separate current-limiting device.

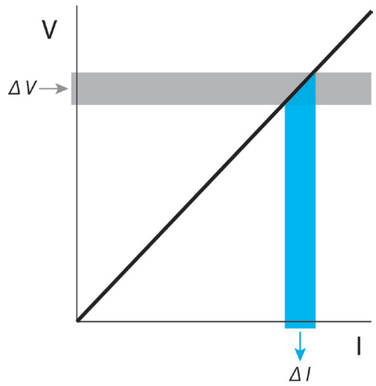



Fig. 13.5 Positive-resistance device (such as an incandescent lamp). With the variation in the mains voltage as indicated by the shaded area, the current is limited correspondingly to the blue area.

24 The glow-switch is here used for creating the voltage ignition peak; it is not used for pre-heating the electrodes.

25 So-called auto-leak transformers are used that also function as current-limiting ballasts.

Gas discharge lamps have a negative-resistance characteristic (Fig. 13.6), meaning that the unlimited current available will increase until the lamp breaks down. By introducing an external resistor in the lamp circuit the current is stabilized (Fig. 13.7).

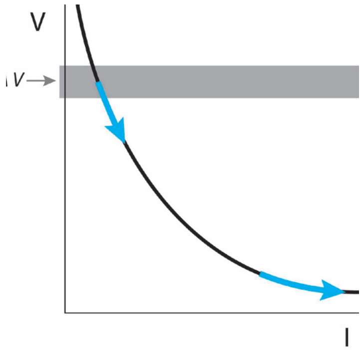



Fig.13.6 Negative-resistance device (such as a gas discharge lamp). At mains voltage supply the current increases until the device breaks down.

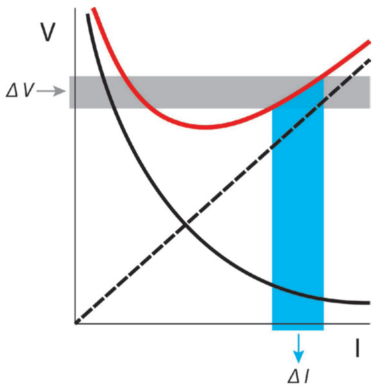



Fig. 13.7 Negative-resistance device with a series resistor in the electrical circuit that stabilizes the current corresponding to blue area. The red curve is the result of adding the positive-resistance resistor (dotted line) to the negative-resistance gas discharge lamp (drawn curve).

Simple resistors can thus be used as current-limiting ballasts for gas discharge lamps. They do, however, dissipate a lot of power and are therefore not normally used. Instead, inductive coils are used, viz. copper wire wound around an iron core. They have the same effect as a resistor, but at much lower power losses in the ballast. [26]

## Re-ignition during the AC mains cycles

The ballast also has to ensure that the lamp continues to operate despite the fact that twice during each frequency cycle of the mains voltage (in Europe 50 Hz and in USA 60 Hz) the current is zero, the lamp off and thus has to be reignited. The re-ignition voltage to re-ignite a warm lamp in operation is lower than the initial voltage peak required for igniting the cold lamp. An inductive ballast system helps to reduce the time the lamp is "off" during each zero passage of the current (in the ideal case to zero). This is because an inductive system shifts the phase between mains voltage and lamp current.

Fig 13.8 shows the effect of the current passing through zero. A consequence of the zero current is that there is no voltage across the ballast and therefore the lamp voltage equals the mains voltage. The top of the figure is for a resistor type of electric lamp circuit having in-phase mains voltage and lamp current. At the moment the current passes through zero, the lamp voltage being equal to the mains voltage is not sufficient to reignite the lamp and the lamp current therefore remains zero (the lamp remains off). Once the mains voltage (and thus the lamp voltage) reaches the reignition voltage, the lamp reignites and the lamp voltage reduces because the ballast voltage is no longer zero. Fig. 13.8 bottom shows the effect of the phase-shift between mains voltage and lamp current of an inductive type of lamp circuit. When the lamp current passes through zero there is already a sufficiently high mains voltage (equal to the lamp voltage) for re-igniting the lamp.

With some lamps the lamp voltage increases through life. The difference between lamp voltage and mains voltage may then become too small to reignite the lamp at zero passage of the current. The lamp remains off until the starter starts the lamp (flickering at end of life).

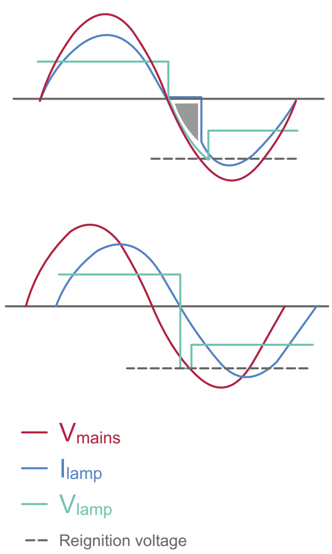



Fig. 13.8 Resistor type of lamp circuit (top): during

26 The power dissipated equals I. r2 with I being the lamp current and r the value of the ohmic resistor. The resistance of a thick coil wire is much lower than that of a normal resistor. Hysteresis in the iron core adds to the dissipated power of the coil, but the final power dissipated is still much less than in a resistor.

zero passage of the lamp current, the lamp voltage, then being equal to the mains voltage, is for a while not sufficient to reignite the lamp. The lamp remains off for the period indicated with the shaded area. In the phase shifted inductive lamp circuit (bottom) there is, at zero current passage, sufficient voltage to reignite the lamp.

### Ballast losses

The actual power losses in a ballast are dependent on the mechanical construction of the ballast and the diameter of the copper windings of its coil.

### Ballast factor

It is now evident that the lumen output of a lamp is dependent not only on the lamp characteristics itself but also on the type of ballast the lamp is operated on. Published lamp characteristics are based on measurements while the lamp is connected to a reference ballast. When a lamp is used on a commercial ballast, the light output of that lamp may be less. The difference is indicated by the ballast factor. This is the percentage of light output from a commercial ballast compared with the light output from the laboratory reference ballast. The ballast factor should be included in the ballast documentation.

### Noise

The magnetic field generated by the coil induces vibrations in the ballast, which in low-quality ballasts leads to disturbingly audible noise (hum). With regard to noise, ballasts are rated in classes A to D, where class A is the quietest class. It is important to use a class of ballast suited to its application.

## 13.2.2 Electromagnetic ballasts

Until the 1980s, all ballasts consisted of a large number of copper windings around an iron core, in accordance with the principle described above. These traditional, or conventional, inductance type of ballasts are called “electromagnetic ballasts” because of the electric and magnetic fields their coils generate. They are sometimes also referred to as “choke ballasts” or “wire-wound ballasts”.

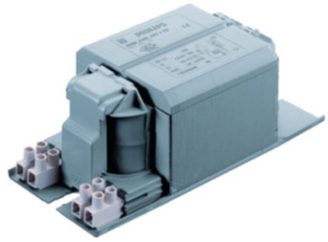


Fig. 13.9 Electromagnetic ballast for a fluorescent lamp (top) and an HID lamp.

### Ballast losses

Power losses in conventional electromagnetic ballasts vary, according to their quality and lamp type, between some 10 and 30 per cent of the nominal wattage of the lamp itself. Until the 1980s, electromagnetic ballasts were the only types available for gas discharge lamps. Since then, more efficient electronic ballasts have been developed for many of these lamps. These electronic ballasts will be dealt with in the following section. Electromagnetic ballasts for fluorescent lamps were banned from the European market as long ago as 2005 by the European commission because of their low energy efficiency relative to that of electronic ballasts.

### Weight and volume

Because of the materials from which they are made (copper and iron), inductive electromagnetic ballasts are both bulky and heavy (Fig.13.9). For example, the size of a fluorescent lamp electromagnetic ballast is at least 25 per cent more and the weight 50 per cent more than that of a modern electronic ballast (see Section 13.2.3).

### Heat management

EElectromagnetic ballasts become hot, and too-high temperatures have a drastically negative effect on ballast life. The maximum permitted temperature of the coil windings, $T_w$, is specified in standards: in Europe, for example, $T_w$ is 130°C. On each ballast housing a $\Delta T$ value is given that specifies the increase in temperature under normal operating conditions. The smaller the value of $\Delta T$, the higher the ambient temperature at which the ballast can be used ($T_{ambient} = T_w - \Delta T$).

### Ballast life

With quality ballasts the average ballast lifetime (85 per cent survival rate) at a switching cycle of 12 hours on and 12 hours off and a ballast-housing temperature of 90° C, is some 50 000 hours. For each 10°C higher temperature, the lifetime is halved.

### 13.2.3 Electronic ballasts for fluorescent lamps

All control-gear devices discussed so far are based on conventional electrical engineering practice. However, modern technology makes it possible to supply the same functions in a more efficient way.

With electronic ballasts for fluorescent lamps:

- lamp-lumen efficacy is increased
- ballast power losses are reduced
- flicker-free light is obtained
- the igniter function is electronically incorporated in the electronic ballast
- lamp lifetime is increased
- weight and volume are greatly reduced
- ballast noise is reduced
- dimming is made easier

#### High-frequency operation

Electronic ballasts electronically transform the sinusoidal 50 Hz mains frequency into a square-wave voltage of higher frequency: hence their name - HF electronic ballasts. The high-frequency voltage lies between 25 000 Hz and 105 000 Hz (viz. 25 kHz - 105 kHz).

#### Ballast losses

HF electronic ballasts work on the same inductive principle as conventional electromagnetic ballasts. At higher frequencies, much smaller coils with correspondingly smaller losses can be used than in conventional electromagnetic ballasts. The power losses of electronic, high- frequency ballasts can be 30 to 50 per cent of the power losses of conventional ballasts. High-frequency power losses in the ballast vary according to ballast quality and lamp type between some 5 and 15 per cent of the nominal wattage of the lamp itself.

The losses are reduced because the impedance (Z) of a coil in an electrical circuit is proportional to the frequency of the current ($Z = 2\ \pi.\ f.\ L$). The higher frequency (f) thus permits the use of a coil with a lower inductance value L, whilst still resulting in the same impedance Z in the circuit, and thus the same current-limiting effect.

#### Lamp-lumen efficacy

When a fluorescent lamp operates on a frequency higher than some 10 kHz, the efficiency with which the radiation is created increases, so that for the same wattage its light output is increased by some 10 per cent (see Fig. 13.10).

With square-shaped voltages of very high frequencies the gas in the discharge tube always remains ionized, also during zero passage of the lamp current. This means that the off-time of the lamp is reduced to zero, effectively increasing the lamp output.

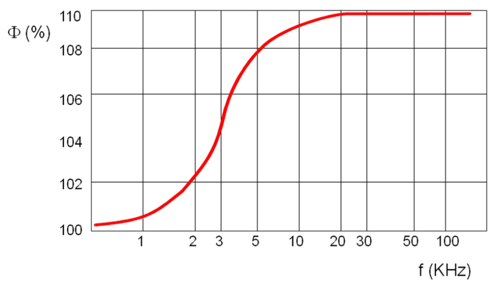



Fig. 13.10 Light output (Φ) of a fluorescent lamp versus the operating frequency (f). 50/60 Hz represents 100% light output.

The more efficient light production combined with the lower ballast losses means that the system efficacy of fluorescent lamps operated at high frequency increases by some 20 to 25 per cent compared to that of the same lamps operated on conventional electromagnetic ballasts. This is why electromagnetic systems for fluorescent lamps are banned in Europe.

#### Frequency range

Fluorescent lamps are operated either on a frequency between 25 kHz and 32 kHz or between 40 kHz and 105 kHz (Fig. 13.11). All dimmable types use the higher frequency range.[27]

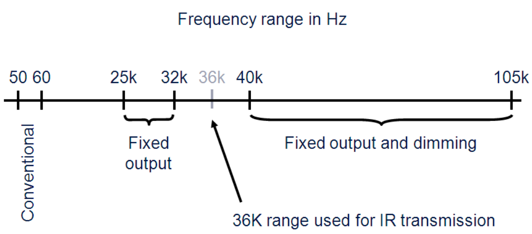



Fig. 13.11 Frequency range used in HF fluorescent lamp electronic ballasts.

27 Frequencies lower than 20 kHz, in the audible frequency range, could lead to "an audible" discharge. The area around 36 kHz has to be avoided because it is the frequency used by IR remote controls and could lead to the lighting interfering with remote-controlled electrical devices.

### Lamp flicker

are "off" twice for a very short time during each cycle of the mains (viz. with a 50 Hz mains 100 times a second and with 60 Hz mains 120 times a second). Since fluorescent powder has a slight lagging effect as regards light output, the visible "ripple" or flicker is hardly noticeable. Nevertheless, for a very small minority of people this flicker causes some problems (eyestrain, headache). At the high frequencies at which HF lamps are operated, lamp flicker is completely absent.

### Ignition

The electronic ignition function is incorporated in the ballast. As with traditional glow-switch starters, the lamp electrodes are normally preheated by the electronic system before the ignition peak is produced.

Special fluorescent lamps with more robust electrodes can be ignited (at a higher peak voltage) without preheating. These so-called cold-start lamps start instantly.

### Lamp life

With electronic operation the exactly-required starting voltage pulse can be accurately supplied to the lamp. This minimizes electrode damage and so considerably increases lamp life. Relative to lamps operated on electromagnetic ballasts, the lamp life is increased by 30 to 50 per cent.

### Weight and volume

The much smaller coil of a high-frequency system compared to that of an electromagnetic system also means that the volume and weight of the ballast is considerably reduced (Fig. 13.12).


Fig. 13.12 Electronic ballast for fluorescent lamps. Below: the internal printed-circuit board.

### Heat management

Electronic ballasts produce much less heat than do electromagnetic ballasts. On the case of each ballast is a test point tc which indicates where the temperature should not exceed a specified value (Fig. 13.13). Luminaire developers should use this point to check that their luminaire satisfies the temperature requirements for the ballast.

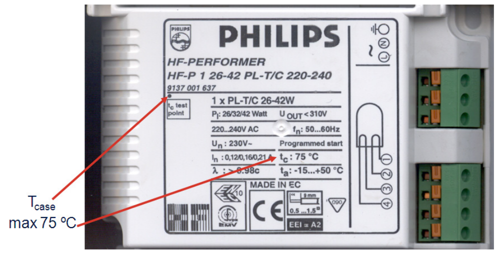



Fig. 13.13 Test point Tc for which the maximum temperature of the ballast case is specified.

### Ballast life

With quality ballasts, the average ballast life (85 per cent survival rate), at a switching cycle 12 hours on and 12 hours off and a ballast case temperature of 75°C, is some 50 000 hours. For each 10°C increase in temperature, the lifetime is halved.

### Noise

Electronic ballasts fall into the best noise restriction class (class D: see Section 13.2)

## 13.2.4 Electronic ballasts for HID lamps

Electronic ballasts for HID lamps have become available only relatively recently and only for some types of HID lamps. Many lower-wattage low and high-pressure sodium and compact metal halide lamps can be operated on electronic ballasts. Some newly-developed HID lamps can be operated only on electronic gear and not on electromagnetic gear. Due to the high currents involved, electronic circuits for lamp powers of more than approximately 400 W are relatively expensive. Such circuits are, however, in development and will come onto the market in the future.

In contrast with HF electronically-operated fluorescent lamps, there is nothing to be gained in terms of improved efficiency in the light-creation process by operating HID lamps on an electronic ballast. Nevertheless, energy savings are obtained, because the power losses in electronic HID ballasts are lower. The advantages of electronically-operated

HID lamps often lie in the better and easier control of certain lamp properties. These advantages are:

- reduced power losses in the ballast
- flicker-free light is obtained
- the igniter function is electronically incorporated in the electronic ballast
- lamp lifetime increases
- much lower weight and volume
- ballast noise is reduced
- dimming becomes possible
- extra control possibilities are obtained, such as constant light output and constant colour, independent of supply-voltage variations
- control of end-of-life behaviour
- signalling of lamp failure becomes a possibility (tele-management), which is especially important in road lighting with lamps spread over a large area.

HID lamps can only be stabilized in certain frequency bands. Outside these restricted bands, the efficiency may drop. Also, the discharge tube may be mechanically damaged by acoustic resonance, or electrodes may break off.

### High-frequency operation

Low-pressure sodium lamps up to 91 W can be operated with an electronic ballast in the high-frequency range of 45 kHz to 55 kHz. These HF-operated SOX lamps have a 15 per cent higher system efficacy than those operated on a traditional ballast system.

### Low-frequency square-wave operation

The operating frequency of the lower-wattage high-pressure sodium and metal halide lamps for which electronic ballasts are available lies between 100 Hz and 200 Hz. Although this is clearly higher than the frequency of the mains, this type of lamp operation is called low-frequency because the frequency is much lower than that used in high-frequency electronic fluorescent lamp and low-pressure sodium lamp systems.

The sinusoidal mains waveform is electronically converted into a square-wave voltage (Fig. 13.14).

Fig.13.14 Square-wave voltage of an electronically operated HID lamp.

### Lumen output and colour stabilization

The electronic system constantly monitors the lamp voltage and regulates the lamp current in such a manner that the lamp power is always constant. Thus the variations in lumen output and colour are greatly reduced during the lifetime of the lamp.

### Ballast losses

At higher frequencies, smaller coils with correspondingly smaller losses can be employed than those used in conventional electromagnetic ballasts. The power losses of electronic HID ballasts can therefore be a factor of 2 lower than those of conventional ballasts. Electronic HID ballast power losses vary according to the quality and lamp type between 5 and 15 per cent of the nominal wattage of the lamp itself. The lamp's system efficacy thus increases by the same percentage.

### Lamp flicker

The frequency range of 100 Hz to 200 Hz is high enough to completely suppress noticeable lamp flicker.

### Ignition

The ignition function is electronically incorporated in the electronic ballast, which simplifies the electrical circuit.

### Lamp life

Electronic operation ensures better control of the ignition. This, together with the constant lamp power of the electronically-operated systems, has a positive effect on the lifetime of the lamps. Lifetime increases by up to 30 per cent compared to traditional electromagnetic operation.

### Weight and volume

As with electronic fluorescent ballasts, the weight and volume of electronic HID ballasts is very much reduced relative to that of conventional electromagnetic ballasts. This is an important advantage, especially in the case of compact lamps (Fig. 13.15).

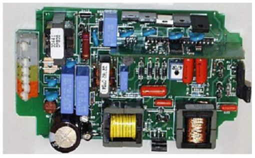


Fig. 13.15 Electronic gear for HID lamps.

### Heat management

Heat-management requirements for HID lamp ballasts are stricter than for electronic fluorescent lamp ballasts because of the lamps are hotter and sometimes of larger power. The electronic ballasts should be shielded from the HID lamp. The temperature at the test point on the ballast, Tc, should never be exceeded (see under "heat management" in the previous Section on electronic fluorescent lamp ballasts).

### Ballast life

With quality ballasts, the average ballast life (85 per cent survival rate), at a switching cycle 12 hours on 12 hours off and a ballast case temperature of 75°C, is some 30 000 hours for compact HID lamps and 50 000 hours for low-pressure sodium lamps.

### Noise

Electronic ballasts fall into the best noise-restriction class (class D: see Section 13.2).

### Control of end of lamp life

At their end of life, some compact HID lamps may show electrical and temperature behaviour that could eventually be damaging for the ballast, the luminaire or the installation. The electronic ballast recognizes this behaviour and switches off the circuit so that no damage can occur.

## 13.3 Dimmers

Dimmers are devices used to adapt the illumination to the actual lighting needs of the moment and to optimize power consumption. Dimming can be done either continuously or in steps. With some lamp types, dimming is not possible because it would negatively affect the performance of the lamp

### 13.3.1 Fluorescent-lamp dimming

### Lamps operated on electromagnetic ballasts

In the case of fluorescent lamps operated on electromagnetic gear, dimming is mostly achieved by a phase-cutting thyristor circuit similar to the ones used for dimming incandescent lamps. A phase-cutting thyristor dimmer cuts part of the AC current waveform during each half-cycle of the 50 Hz (or in the USA 60 Hz) mains cycle (Fig. 13.16). During the time that the current is cut and the lamp is temporarily off, no power is dissipated, so saving energy while reducing the light output.

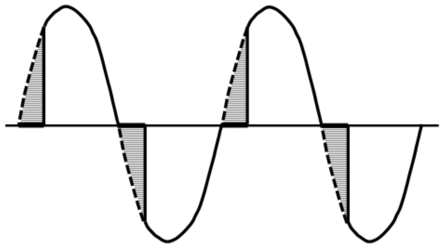


Fig. 13.16 Phase cutting of AC current.

TThyristor dimmers are small and inexpensive. Practically any type of fluorescent lamp can be dimmed down to about 50 per cent of its nominal light output. However, when dimming to below 50 per cent of the nominal current, the discharge will no longer provide sufficient heat to keep the electrodes at the proper electron-emission temperature, so continuous electrode heating becomes necessary. The heating current must be independent of the lamp current, which means that a separate heating transformer will be required, making the system much more complicated.

Fluorescent lamps operated on electromagnetic ballasts can also be dimmed by switching an extra inductive coil (in the form of an extra second ballast) in series with the normal ballast. Only one dim step is possible, and the dimming is less efficient than with phase-cutting dimming. This is sometimes done to switch fluorescent-lamp street-lighting luminaires to half lighting level after a certain time in the evening or night.

### Lamps operated on electronic ballasts

Fluorescent lamps operated on electronic high-frequency dimmers are dimmed by increasing the frequency of the supply current.[28] Provided the electronic ballast circuit provides sufficient heat to keep the electrodes at the proper electron emission temperature, lamps can be dimmed to less than

28 The impedance of the small inductive coil in the lamp circuit increases with increase in frequency, so decreasing the lamp current. With the decrease in lamp current both the light output and dissipated power decrease as well.

one per cent of their nominal light output. This means that both lamp electrodes must be accessible to the dimming circuitry in order to enable the electronic dimmer to control the electric current flowing through them. This is always the case with normal tubular fluorescent lamps, but with compact fluorescent lamps it is only possible with the 4-pin versions.

### 13.3.2 HID lamp dimming

Not all HID lamps can be dimmed. For example, with low-pressure sodium lamps the operating temperature when dimmed would decrease so much that they would extinguish. And with high-pressure mercury and high-wattage metal halide lamps, there would be an unacceptable colour shift and lamp life would be negatively affected. However, most high-pressure sodium and some compact metal halide lamps can be dimmed.

#### Lamps on electromagnetic ballasts

One-step dimming of high-pressure sodium lamps can be simply obtained by switching a coil, in the form of an extra ballast, in series with the normal ballast. This increases the impedance of the circuit, so decreasing the lamp current and, as a result of this, the light output and the lamp. In this way the lamp can be dimmed in one step to approximately 50 per cent light output at 65 per cent power. Further dimming would result in an unacceptable colour shift towards the yellow-orange part of the spectrum. This method is often used in road-lighting installations to dim the lighting at a certain time in the evening or night.

This "twin-ballast" system can be combined with an electronic controller that employs phase cutting to regulate light output whilst almost preserving the sinusoidal shape of the lamp current. In this way, some high-pressure sodium lamps can be continuously dimmed down to 20 per cent (at 35 per cent power).

#### Lamps on electronic ballasts

Lower-wattage high-pressure sodium lamps and some of the compact metal halide lamps (including the versions specifically developed for use in road lighting) operated on electronic ballasts, can be dimmed by regulating the frequency of the supply (similar to dimming HF electronic fluorescent lamp systems).[29] Dimming can be continuous from 100 per cent down to some 20 per cent (the latter at 35 % power).

Because of slow warm-up and hot-re-ignition delay of HID lamps, all dimming methods (including those for electromagnetic systems) employ an automatic procedure whereby the lamp is started at full power and any dimming is delayed by 3 to 10 minutes until the lamp is fully heated and stabilised.

## 13.4 Harmonic distortion

In gas discharge lamps (as in solid-state light sources) the mains-current waveform becomes distorted, viz. it is no longer purely sinusoidal (Fig. 13.17).

> Some of the reasons for this are the ignition peaks during starting of the lamp and re-ignition peaks during zero passage of the current, the use of phase-cutting dimming systems and, as we will see in the next Chapter, the need with LEDs to provide voltage transformation from AC mains to DC low voltage.

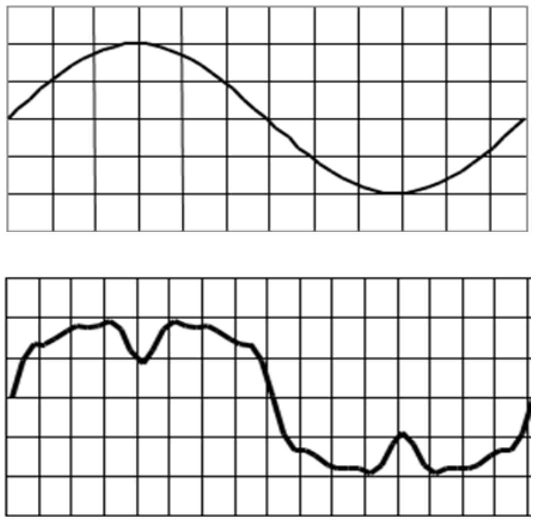


Fig.13.17 Ideal and distorted waveforms

Distortion of the waveform is called harmonic distortion. Harmonic distortion may have a negative influence on the power qquality of the electricity network to which the lamp system is connected. This may lead to an extra energy load and to incorrect functioning of electrical equipment that makes use of the same electricity network. To protect the network, the total harmonic distortion caused by a lamp circuit has to be limited. For this reason electronic filters have to be incorporated in the circuit to block the passage of higher harmonic currents. In modern fluorescent lamp circuits (including those for compact fluorescent lamps) harmonic distortion is usually adequately limited. In LED circuits (see next Chapter) the quality of the harmonic distortion limitation of commercially-available LED systems today varies from poor to more than sufficient.

29 The impedance of the ballast coil of the electronic circuit increases by changing to a higher frequency. The lamp current decreases and with it the light output and the power of the system.

The term harmonic distortion comes from the fact that the distorted current in fact consists of a great number of lower-amplitude sinusoidal (harmonic) waves of frequencies higher than those of the mains frequency. The higher harmonics are multiples of the fundamental frequency of the mains (50 Hz or 60 Hz) and are numbered sequentially. Fig. 13.18 shows the sine waves (harmonics) that add up to the distorted square wave.

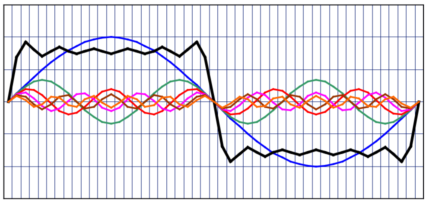
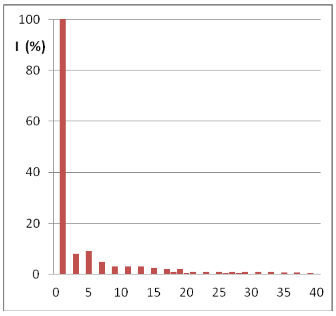


Fig. 13.18 The different sine waves (harmonics), drawn in colours, add up to the distorted, near-square wave drawn in black. The blue sine wave shows the fundamental curve of the mains (first harmonic), while the green one is the third harmonic.

The higher-frequency currents (higher harmonics) all result in a different impedance from coils and capacitors in the electrical lamp-gear system. As a result, some current harmonics can flow back into the electricity network and subsequently have a (disturbing) influence on other devices connected to that network. The third harmonic, in particular (with a frequency of 150 Hz for a 50 Hz mains-supply system and 180 Hz for a 60 Hz mains-supply system), has a negative effect because it flows through the neutral wire of the electricity net. Fig. 13.19 shows an example of the harmonic currents created in a poor-quality LED and in a good-quality LED system, respectively.



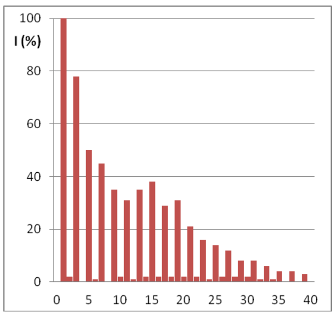




Fig 13.19 Relative harmonic currents of a low-quality LED (top) and a high-quality LED (bottom).

## 13.5 Power factor

As we have already seen, the inductive operation of lamps (as in electromagnetic and electronic ballast systems) shifts the phase of the lamp current relative to that of the mains voltage. This shift is called phase shift – the actual shift is indicated by the angle φ in Fig. 13.20.

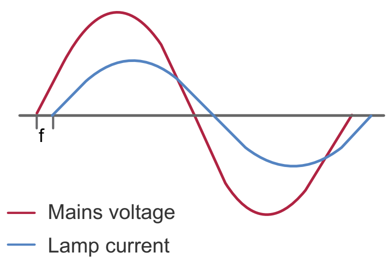



Fig. 13.20 Phase shift φ between mains and lamp current of an inductive system.

A large phase shift is undesirable, because for the same power consumption a higher current is drawn through the wiring and through the cables of the electricity network. The electricity companies cannot easily measure the stronger current and therefore do not get paid for all the energy that they deliver.

The ratio of the measured power to the total power drawn by the system is called the power factor P. The power factor is a factor between 0 and 1 and is equal to the cosine φ of the phase shift:

P = measured power / drawn power. [30]

For the mains-frequency voltage and current the power factor P = cos (φ).

Electricity companies require, especially for the higher-wattage lamps, that the power factor is above a certain value. Table 13.1 gives limits set by the International Electrotechnical Committee (IEC).

30 The part of the power that is not measured is stored in capacitors or creates magnetic fields around coils.

| Lamp power | < 2 W | 2 W - 5 W | 5 W – 25 W | > 25 W |
|---|---|---|---|---|
| External ballast / driver | no limit | no limit | cos (φ) ≥ 0.7 | cos (φ) ≥ 0.9 |
| Integrated ballast / driver | no limit | cos (φ) ≥ 0.4 | cos (φ) ≥ 0.7 | cos (φ) ≥ 0.9 |

Table 13.1 Limits for cos (φ) set by the IEC.

Power-factor correction (or as it is usually called, power-factor compensation) is often done by placing a capacitor (Fig. 13.21) in parallel or in series with the lamp. This works because capacitive systems shift the current in the opposite direction to inductive systems. Harmonic distortion (see Section 13.4) makes accurate compensation more complicated or even impossible because it has to be done for all harmonics. This is one of the reasons for limiting harmonic distortion itself. With some lamps the phase shift, and thus the power factor, changes over the lifetime of the lamps. Such lamps therefore call for a more complicated power- factor compensation.

Fig.13.21 Capacitor for power-factor compensation.

## 13.6 Suppression of Electromagnetic Interference (EMI)

Electrical and electronic devices may emit unwanted electromagnetic radiation. Even switching a simple switch on and off produces such (unwanted) radiation. This electromagnetic radiation may interfere with other electrical or electronic devices such as computers, radios and televisions. Also, gas discharge lamp circuits, especially those used on electronic ballasts, may emit unwanted electromagnetic radiation that causes interference problems. For example, some early laboratory types of electronic compact fluorescent lamps interfered with nearby television sets (switching them on or off). Today, in order to prevent electromagnetic interference problems, all countries or regions have requirements to restrict radiation levels. Control gear for lamps should take care that lamp circuits strictly comply with these EMI requirements.

# 14 Electrical control gear for LEDs

## 14.1 Basics

Like gas discharge lamps, solid-state lamps can also not function when they are operated direct from the mains-supply voltage. Instant starting is no problem with solid-state lamps, but the mains supply has to be rectified and transformed to a lower voltage and measures have to be taken to ensure that the current through the light source is constant. The electrical control gear employed for this purpose is usually referred to as the driver. The dimming function, where relevant, can be a separate device or can be incorporated in the driver.

Issues such as harmonic distortion, power factor and electromagnetic interference (EMI) are the same as with gas discharge lamps. For these aspects we therefore refer the reader to the relevant sections in the previous chapter about control gear for gas discharge lamps.

### 14.1.1 Rectified low voltage

Solid-state light sources are low-voltage rectifiers that allow current to pass in one direction only. This means that the AC mains supply has to be transformed to low voltage and then rectified into a DC supply.

### 14.1.2 Constant current

Although a solid-state light source has a positive resistance characteristic, the voltage-current dependency is exponential in the area of operation (see flat area in Fig. 14.1). Small fluctuations in supply voltage therefore cause large variations in current that can damage the light source. A simple series resistor in the electrical circuit stabilizes the current to create, in fact, a "constant" current supply (Fig. 14.2). In practice only miniature indicator LEDs use such a resistor for stabilizing the current. High-power LEDs use an electronic driver to obtain a similar, constant-current, characteristic.

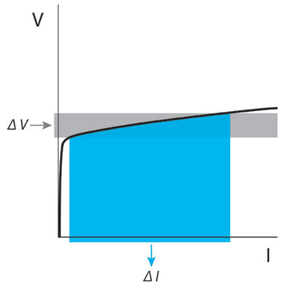



Fig. 14.1 Voltage (V)-current (I) dependency of solid-state light sources. Small fluctuations in supply voltage (grey area) result in large variations of current (blue area).

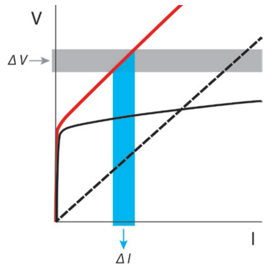



Fig. 14.2 Principle of a constant-current supply for solid-state light sources that stabilizes current in spite of voltage variations. In this example, with a series resistor. Red curve: combined effect of LED with resistor in series.

## 14.2 Electronic drivers

All high-power, high-brightness LEDs employ electronic ballasts, usually referred to as drivers (Fig. 14.3) because so much energy is lost in resistor-type drivers. The electronic ballasts provide for the transformation from high voltage to low voltage, for rectification and for the constant current supply.

Fig. 14.3 Example of an electronic LED driver.

### 14.2.1 On-chip driver

In the laboratory, LEDs have been produced where the driver, in the form of a chip, is mounted on the LED chip itself. This just shows how far miniaturization with LEDs is likely to go.

### 14.2.2 Driver losses

Power losses in electronic drivers vary, according to their quality, between approximately 10 and 30 per cent. Losses in poor quality drivers can be as much as 50 per cent of the nominal wattage of the LED itself. It is, of course, important to take these losses into account when specifying luminous efficacies for LEDs – which, unfortunately, is not always done.

## 14.3 Dimmers

Most LED drivers with an integrated dimming function use pulse-width modulation (PWM) to regulate the power to the LED. Just as with phase-cutting dimming for incandescent and fluorescent lamps, pulse-width modulation turns the LED on and off rapidly, reducing the "on-time" to achieve the desired dimming level. The speed with which this is done (with LEDs usually between 150 Hz and 400 Hz) is so fast that the human eye does not see the flickering of the light. The longer the "off" periods are relative to the "on" periods (pulse width), the more the LEDs are dimmed (Fig.14.4). The smallest pulse width that can be switched by the system determines the lowest dimming level: often approximately five per cent. A relatively simple electronic timer provides the switching off-and-on function. During the "on" pulse, the current is kept at the rated value for which the LED is designed, so that dimming has no negative effects on the operation of the LED, and consequently no negative effects on lifetime.

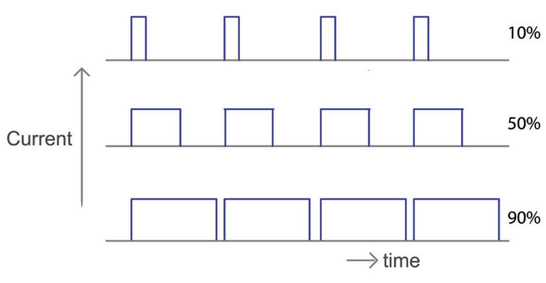



Fig. 14.4 Pulse-width modulation (PWM) used to dim LEDs.

Not all retrofit LED lamps can be dimmed on normal, commercially-available dimmers: not even if these dimmers make use of phase cutting. The design of retrofit LED lamps that are dimmable with common dimmers is difficult because of the wide differences in performance of these dimmers. For this to be possible, the built-in electronic driver has to be specifically designed. Retrofit LED lamps that are designed to be dimmed on normal commercial dimmers have a notice to this effect on their packaging.

## 14.4 Harmonic distortion

Limitation of harmonic distortion with LED circuits to protect the electricity network is just as important as with gas discharge systems. Details have been discussed in Section 13.4.

## 14.5 Power factor

Limitation of the power factor in LED circuits, to limit the electric current in the electricity network and to enable correct charging of electricity costs, is just as important as with gas discharge electrical circuits. Details have been discussed in Section 13.5.

## 14.6 Suppression of Electromagnetic Interference (EMI)

Just as with gas discharge lamps, suppression of electromagnetic radiation that may interfere with other electrical devices has to be limited in LED circuits. Details have been discussed in Section 13.6..

# 15 Luminaires

A luminaire is a device that controls the distribution of the light emitted by a lamp or lamps and that includes all the items necessary for fixing and protecting the lamps (and sometimes the gear, too) and for connecting them to the electricity-supply circuit. In American English, the term fixture is usually used instead of luminaire, while in Anglo-Saxon countries, the term fitting is also sometimes used instead of luminaire.

The principal characteristics of luminaires can be listed under the following headings:

- Optical
- Mechanical
- Electrical
- Thermal
- Aesthetics

Luminaire characteristics are widely different for the different areas of lighting application, namely indoor general lighting, indoor accent lighting, road lighting, and flood lighting. These differences also call for different types of photometric documentation.

## 15.1 Optical characteristics

The optical characteristics of a luminaire determine the shape of its light beam, or light-output distribution. The light distribution of a luminaire defines how the luminous flux radiated by the lamp or lamps is distributed in the various directions within the space around it. Different lighting applications require different light distributions and thus different luminaires.

The desired light distribution of a luminaire is obtained through the application of one or more of the physical phenomena: reflection, refraction, and diffuse transmission. Many luminaires also make use of shielding in one form or another, principally to obtain the required degree of glare control and to limit light pollution. The shielding function may be performed by refractors or diffusers or by mirror reflectors, by white-painted surfaces or, where very stringent glare control is required, by black surfaces. Typical techniques employed to control light distribution are illustrated in Fig. 15.2 on the basis of road-lighting examples.

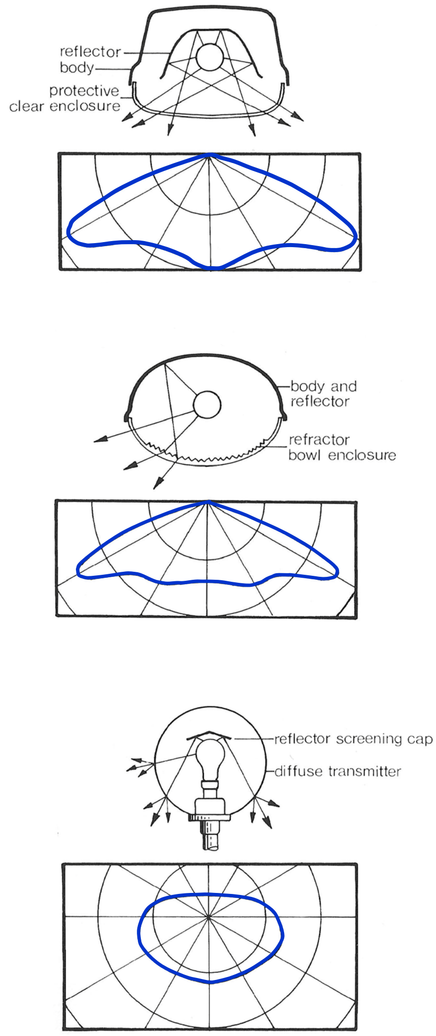



Fig. 15.2 Control of light by means of reflection and screening by the reflector and by the luminaire's body (top), by refraction and screening by the luminaire's reflector body (middle), and by diffusion through an opal enclosure and screening by reflector cap (bottom).

### 15.1.1 Reflectors

Many conventional luminaires are provided with a reflector (sometimes in conjunction with another light-control element) in order to create the appropriate light distribution. The reflecting material that is used for reflectors can be specular, spread or diffuse (Fig. 15.3).

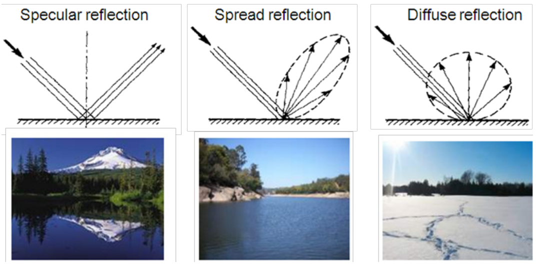



Fig. 15.3 The three basic types of reflection.

## Specular reflectors

Specular reflectors (also called high-gloss mirror reflectors) are used when a precise form of light distribution is required, as in floodlights, spotlights and road-lighting luminaires. The reflector creates multiple images of the light source. The most widely used material is sheet aluminium, which has the strength needed to produce a stable reflector. To obtain a highly-specular finish, the aluminium is polished: mechanically, chemically, electrolytically, or by a combination of these processes. Reflectance values are around 0.70. Alternatively, commercial- grade aluminium can be clad with a thin layer of super-purity aluminium or silver. With aluminium, reflectance values of up to 0.80 can be obtained, while with silver a reflectance of more than 0.90 is possible. Finally, there is vacuum metalising, in which a specular layer of aluminium is deposited on a suitably-smooth substrate (metal, glass or plastics).The resulting reflectance, which is somewhere between 0.80 and 0.90, is dependent on both the substrate material and the quality of the metalising process.

## Spread reflectors

With spread reflectors (sometimes also called half-matt reflectors) there is no sharp mirror image of the light source. They are employed where a moderate degree of optical control is required, with the emphasis on producing a beam with smooth transitions. Such reflectors also help to smooth out discontinuities in the light distribution caused by inaccuracies in the shape of the reflector. Spread reflection is produced by hammering very small dimples and bumps into a specular surface or by brushing or etching it (Fig. 15.4).

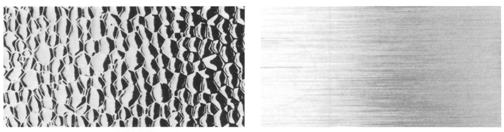


Fig. 15.4 A spread finish as produced by hammering (left) or by brushing (right) a specular surface.

## Diffuse reflectors

At the other extreme from specular reflection is diffuse reflection, which is also called matt reflection. Here light incident on the reflector is scattered in all directions, so there is no mirror image of the light source. Matt reflectors cannot provide sharp beam control, but are employed where diffuse or non-focused light distributions are required. Matt-finished metals and white glossy paints on metal or glossy-white plastics provide near-diffuse reflection. The small specular component due to the gloss is of no practical optical significance; the gloss merely serves to facilitate cleaning. Reflectance values can be in the range 0.85 to 0.90. Ceramic materials or finishes have completely-diffuse reflection characteristics with extremely high reflectances of up to 0.98.

## Reflector forms

There are three basic reflector forms: plane, curved, and facetted. (Fig.15.5).

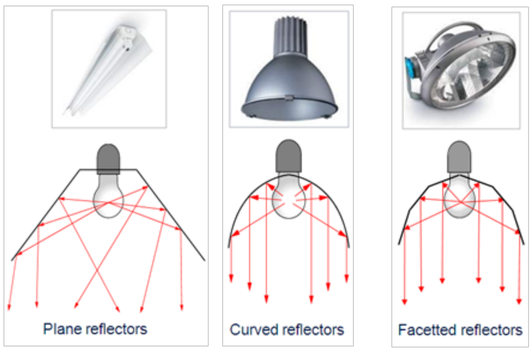



Fig. 15.5 Basic reflector forms.

### *Plane reflectors*

When using a simple plane, or straight-sided, reflector the light emitted by the light source is reflected according to the material of the reflecting surface, viz. specularly or diffusely.

Plane reflectors are often used to screen off the direct light from the light source. Accurate beam shaping is not very well possible with plane reflectors, but by changing the symmetry of the reflectors, the direction in which the bulk of the light is emitted can be changed.

### *Curved reflectors*

The best optical performance is obtained when using a curved reflector. Depending on the curvature, many different types of beams can be created. A curved reflector may be cylindrical, parabolic, elliptical, hyperbolic, or some other contour to suit a particular application. The circular and parabolically-shaped reflectors are the ones most commonly used. In some cases, these shapes can be combined (Fig.15.6).

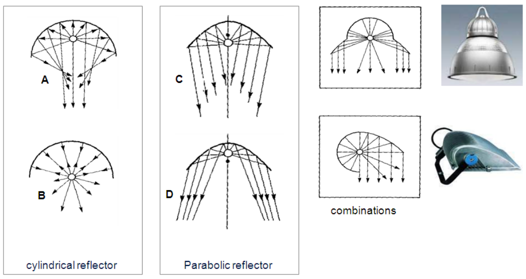



Fig. 15.6 Cylindrical, parabolic and combinations of circular and parabolic reflector shapes.

The most important optical property of a parabolic reflector is that a point source of light placed in its focus will produce a parallel beam of reflected rays with the greatest intensity in its centre. If the light source is not at the focus but in front or behind it, the reflected rays are no longer parallel. (Fig. 15.6 C and D). Thus, by choosing the position of the light source relative to the focus point, the desired beam shape (narrow to wide) can be created. Since a lamp is never a real point source, deviations from the theoretical beam shape for a point light source. as sketched above, will always occur. The smaller the light source relative to the size of the reflector, the more accurately can the beam be shaped.

*Facetted reflectors*

Smooth-curved reflectors have to be produced to a high degree of accuracy, because even small deviations from their intended shape will produce undesirable discontinuities in their light distribution (striations). This will not occur with a facetted reflector. A facetted reflector consists of a number of adjacent, plane or curved, facets that together approximate a curve, as in Fig. 15.5 right, that is an approximation of a parabolic curve. The width of beam produced by the facetted reflector is somewhat greater than that of a smooth-curved refelctor.

### 15.1.2 Refractors

Refractors are used to create the desired luminaire light distribution by passing the light from the source through a refractor (Fig. 15.7). The angle through which the light is bent is dependent on both the shape of the refractive material and its refractive index (Snell's law).

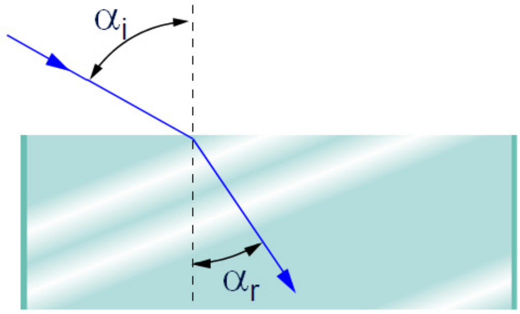



Fig. 15.7 Bending of light by refraction (according to Snell's law) from the incident $\alpha_i$ to the refraction $\alpha_r$.

Refracting devices are either lenses or prisms. The type of refractor most commonly employed in indoor lighting is the lens found in tubular fluorescent lamp luminaires intended for general lighting (Fig. 15.8). It consists of a horizontal plastic panel which is mounted just below the lamp. The panel is flat on the top and has a special pyramidal (prism) or lens structure on the underside, which directs the light in certain directions and reduces the brightness under specific angles. Where in the past prismatic controllers were used with relatively large-sized prisms, we see today more advanced micro-prism or micro-lens-type refractors that give more accurate possibilities to shape the light distribution. These types of refractors are also used to produce LED luminaires for general indoor lighting and for road lighting (Fig. 15.9). Refracting glass bowls were in the past sometimes used for high-pressure mercury and sodium road-lighting luminaires. They have become obsolete because they are heavy, but more so because lighting control in the upwards direction, and therefore control of light pollution, is not easily attainable.

Fig. 15.8 Micro-lens type of refractor for a LED luminaire for general indoor lighting.

Fig. 15.9 LED road-lighting luminaire with lenses (bottom: enlarged lens panel).

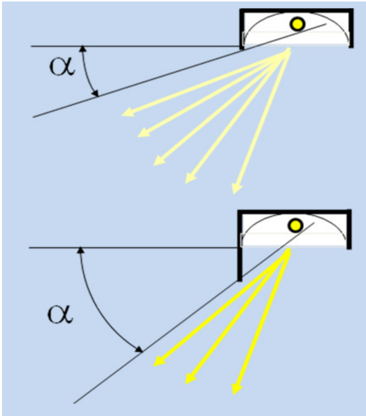




Fig. 15.11 Luminaire screening as defined by screening angle α.

### 15.1.3 Diffusers

Translucent diffusers enlarge the apparent size of the light source. They scatter the light of the lamp in all directions without defining its light distribution. They serve mainly to reduce the brightness of the luminaire and thus the glare created by it. Diffusers are made of opal glass or translucent plastic, commonly acrylic or polycarbonate (Fig. 15.10). The material should be such that it scatters the light whilst producing the minimum amount of absorption.

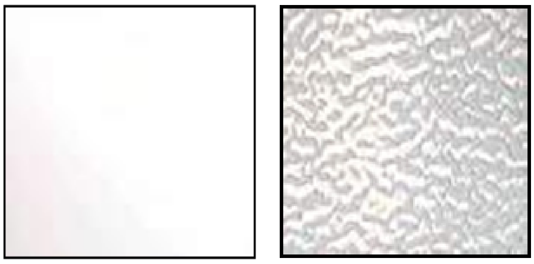


Fig. 15.10 Two different types of translucent diffuser.

The luminaire reflector housing itself, or a built-in baffle, can provide the screening function (Fig. 15.12). When the sole purpose of the louvre is to shield the lamp from view, diffuse-reflecting material is used, such as a white-plastic louvre or, in the case of floodlights, matt-black metal rings (Fig. 15.13).

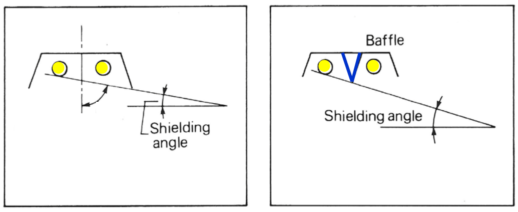




Fig. 15.12 Lamp shielding by the reflector itself (left) and by an internal baffle (right).

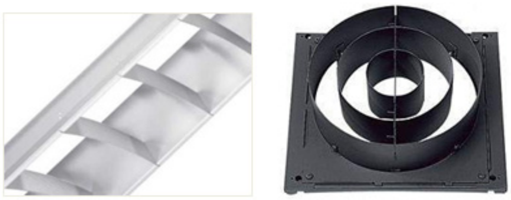


Fig. 15.13 Simple louvre (left) to shield the lamp in a fluorescent-lamp luminaire, and (right) a floodlight louvre.

### 15.1.4 Screenings

#### Screening the lamp from direct view

Screening is employed to hide the bright lamp or lamps from direct view. The degree to which a lamp is hidden from view is expressed by the shielding angle α: the larger the shielding angle, the better the degree of shielding (Fig. 5.11). The higher the brightness (luminance) of the lamp, the more strict are the requirements for the shielding angle (viz. larger shielding angle required).

Shielding devices are often combined with the function of defining the light distribution, in which case highly-reflective material is used for the louvre. In luminaires for fluorescent lamps, relatively cheap flat-profile reflector louvres are often used to shield the lamp from direct view when viewed lengthwise (Fig. 15.14 left). Parabolic reflector louvres, in addition to screening the lamp from direct view, also redirect the light downward thus improving the efficiency of the luminaire because the light refected from the louvre effectively contributes to defining the light distribution (Fig. 15.14 right).

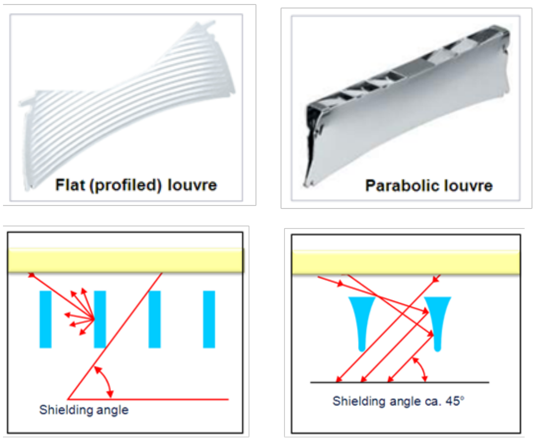



Fig. 15.14 Flat-profile louvre elements (top) and parapolic louvre (bottom).

**Prevention of disturbing reflections in display screens**

With poorly-designed indoor-lighting luminaires it is not just a direct view of the lamps that can be disturbing, but also the fact that the lamps can produce disturbing reflections in visual-display (e.g. computer) screens. With poor-quality screens in particular, these reflections may hamper legibility. However, the louvres needed for shielding the lamp from direct view can be so designed that these disturbing reflections are minimized for all directions around the luminaire Fig. 15.15. (Philips term: Omni-directional Luminance Control, OLC).

Fig. 15.15 Louvre design that provides omni-directional control of disturbing reflections in display screens.

## 15.1.5 Colour filters

In certain lighting applications, in particular display lighting and decorative floodlighting, colour is sometimes used to help achieve the desired aesthetic effect. In the past, colour filters attached to luminaires containing white light sources were extensively used for this purpose. Both absorption and dichroic (interference) filters were used, although absorption filters in particular (Fig. 15.16) lower the efficacy of the total lighting system. Typical transmittance values are, for blue absorption filters 5 per cent, for green absorption filters 15 per cent, and for red absorption filters 20 per cent. The consequence of the light absorption is that these filters become warm, which with high-power floodlights may damage the filter. The solution where such floodlights are employed is to use dichroic filters, which are a more expensive alternative. Today, coloured LED light sources are normally employed where coloured lighting is required. Here the colour comes directly from the lamp itself, so the efficacy of the lighting system is much higher.

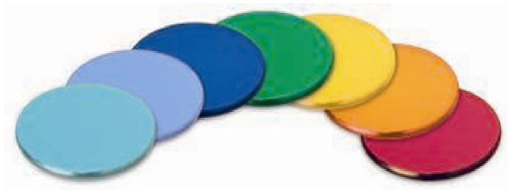


Fig. 15.16 Absorption-type colour filters.

## 15.2 Light-distribution characteristics

The light distribution of a luminaire defines how the luminous flux radiated by the luminaire is distributed in the various directions within the space around it. This is also called luminous intensity distribution, since it is specified in terms of luminous intensities in all the directions in which the luminaire radiates its light (Fig. 15.17). The luminous intensity diagram can be thought of as "the light fingerprint" of a luminaire, in digital form (I-Table), and is the basis of all lighting calculations.

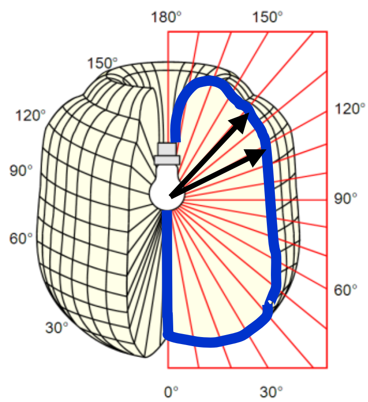



Fig. 15.17 Light distribution of a luminaire given by its luminous intensity diagram. The arrows represent the luminous intensities (I) in the directions specified. Here the light distribution is given for all planes, although it is usually only given for one (e.g. the blue curve) or two, mutually perpendicular, planes.

Basic photometric data that can be calculated from the light distribution are the beam spread and the luminaire light output ratio. For all types of luminaires and for all types of application these data provide an insight into the photometric quality of the luminaire. Closely related to this data are application-specific photometric data, as contained in iso-illuminance and iso-luminance diagrams, work-space utilisation factors, road-surface luminance and illuminance yield factors, and glare-specific diagrams. These application-specific photometric data will not be dealt with in this book. The basic photometric data will be described in more detail in the following paragraphs.

### 15.2.1 Coordinate system

To specify the complete light distribution (luminous intensity distribution) of a luminaire in all directions, two different standardised systems of co-ordinates are employed. The actual system chosen depends on the type of luminaire, the type of lamp, the way the luminaire is mounted in normal use, and its application. The right choice of system facilitates the measurement process and simplifies subsequent lighting calculations. Usually, the system used for indoor and road- lighting luminaires is the so-called C-Gamma abbreviated to C-γ system, and for floodlights the B-Beta abbreviated to B-β system.

#### C-γ system of coordinates

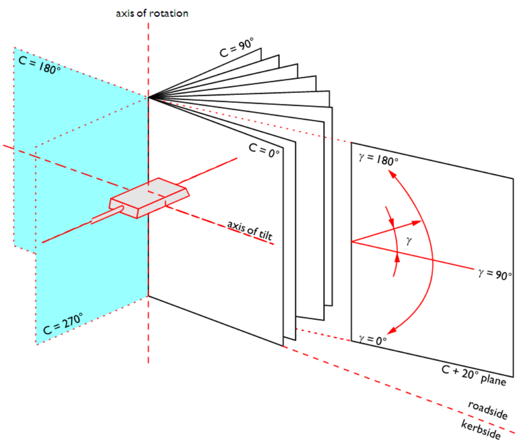



Fig.15.18 The C-Gamma system of coordinates used for representing the light distribution of a luminaire.

In the C-γ system of co-ordinates the axis of rotation of the C-planes is vertical and passes through the centre of the luminaire (Fig. 15.18). The position of a particular C-plane is defined by the included angle C (0° to 360°) between it and the C = 0° reference plane.[31] A direction in a particular C-plane is indicated by the angle Gamma (γ), which ranges from 0° (down) to 180° (up).

#### Luminous intensity (I) table

The luminous intensity or I-Table of a luminaire is the digital form of the light distribution of a luminaire and is the basic input for all lighting-calculation software. It is specified in the C – Gamma co-ordinate system (Table 15.1).

C/GAMMA I-TABEL

| PLANE---> C / ANGLE = γ | 270.0 | 285.0 | 300.0 | 310.0 | 315.0 | 320.0 | 325.0 | 330.0 | 335.0 | 340.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 159.0 | 159.0 | 159.0 | 159.0 | 159.0 | 159.0 | 159.0 | 159.0 | 159.0 | 159.0 |
| 10.0 | 156.3 | 161.5 | 164.8 | 165.6 | 165.9 | 165.8 | 165.3 | 164.8 | 164.3 | 163.5 |
| 20.0 | 144.2 | 149.6 | 152.2 | 153.3 | 154.1 | 155.5 | 158.0 | 159.4 | 160.2 | 160.7 |
| 30.0 | 124.0 | 127.0 | 136.2 | 144.9 | 149.9 | 154.3 | 158.4 | 161.7 | 163.5 | 164.5 |
| 35.0 | 113.0 | 116.2 | 129.4 | 142.5 | 149.3 | 155.3 | 160.4 | 164.2 | 165.5 | 166.5 |
| 40.0 | 102.3 | 105.9 | 122.7 | 139.7 | 148.5 | 156.7 | 162.0 | 165.6 | 167.3 | 168.4 |
| 45.0 | 93.0 | 96.5 | 116.8 | 136.8 | 146.3 | 184.1 | 161.5 | 166.5 | 168.8 | 170.3 |
| 47.5 | 88.0 | 92.2 | 114.4 | 135.5 | 144.7 | 153.0 | 161.2 | 167.3 | 169.8 | 171.4 |
| 50.0 | 83.0 | 88.1 | 111.7 | 134.1 | 143.4 | 152.4 | 161.2 | 168.5 | 171.0 | 172.8 |
| 52.5 | 78.0 | 83.8 | 108.5 | 132.2 | 142.0 | 151.9 | 161.6 | 169.3 | 172.6 | 174.6 |
| 55.0 | 72.8 | 79.4 | 105.5 | 129.6 | 141.1 | 152.3 | 163.1 | 171.7 | 175.3 | 177.5 |
| 57.5 | 67.5 | 74.9 | 102.6 | 127.6 | 140.7 | 153.6 | 165.8 | 176.4 | 180.9 | 181.8 |
| 60.0 | 62.0 | 70.2 | 100.0 | 126.6 | 142.3 | 157.9 | 169.8 | 185.6 | 191.9 | 192.3 |
| 62.5 | 57.0 | 65.7 | 97.9 | 128.7 | 148.0 | 167.4 | 186.5 | 203.1 | 207.4 | 208.0 |
| 65.0 | 51.8 | 61.4 | 97.6 | 134.6 | 157.9 | 181.9 | 202.8 | 217.8 | 222.9 | 224.2 |
| 67.5 | 46.5 | 58.0 | 99.0 | 144.5 | 174.3 | 202.4 | 214.1 | 223.3 | 230.3 | 230.3 |
| 70.0 | 41.2 | 55.1 | 101.8 | 155.1 | 185.6 | 215.1 | 211.5 | 211.7 | 215.6 | 211.7 |
| 72.5 | 36.0 | 52.7 | 103.5 | 159.1 | 179.7 | 192.7 | 184.4 | 176.0 | 174.3 | 167.3 |
| 75.0 | 31.0 | 50.7 | 102.3 | 149.4 | 155.4 | 149.2 | 133.9 | 119.6 | 112.7 | 111.9 |
| 77.5 | 27.5 | 46.2 | 96.6 | 126.8 | 119.8 | 102.5 | 90.2 | 77.7 | 70.9 | 71.4 |
| 80.0 | 24.0 | 40.5 | 84.0 | 98.9 | 84.9 | 66.0 | 60.1 | 53.7 | 50.9 | 49.9 |
| 82.5 | 20.5 | 34.0 | 70.2 | 72.0 | 60.7 | 47.9 | 42.4 | 39.7 | 38.6 | 37.9 |
| 85.0 | 17.0 | 27.4 | 55.8 | 49.2 | 41.7 | 34.6 | 31.3 | 29.1 | 28.6 | 27.9 |
| 87.5 | 13.5 | 21.4 | 41.3 | 31.2 | 27.4 | 24.5 | 22.9 | 21.6 | 21.3 | 21.1 |
| 90.0 | 10.0 | 16.0 | 27.0 | 18.7 | 17.5 | 16.9 | 16.0 | 15.0 | 14.9 | 14.8 |
| 92.5 | 8.5 | 13.4 | 20.5 | 15.7 | 14.7 | 14.0 | 13.3 | 12.5 | 12.4 | 12.3 |
| 95.0 | 6.3 | 9.6 | 15.7 | 13.4 | 12.5 | 11.7 | 11.1 | 10.5 | 10.3 | 10.0 |
| 97.5 | 3.5 | 5.0 | 12.4 | 11.5 | 10.8 | 10.1 | 9.9 | 10.0 | 9.8 | 9.7 |
| 100.0 | 1.2 | 1.3 | 10.1 | 10.0 | 9.5 | 9.1 | 9.4 | 9.8 | 9.5 | 0.0 |
| 102.5 | 0.0 | 0.0 | 8.5 | 8.8 | 8.4 | 8.3 | 8.9 | 6.0 | 0.0 | 0.0 |
| 105.0 | 0.0 | 0.0 | 6.8 | 7.7 | 7.7 | 7.4 | 2.8 | 0.0 | 0.0 | 0.0 |
| 120.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 135.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 150.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 165.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 180.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 15.1 Part of a table of luminous intensity values for a specific luminaire.

#### B-β system of coordinates

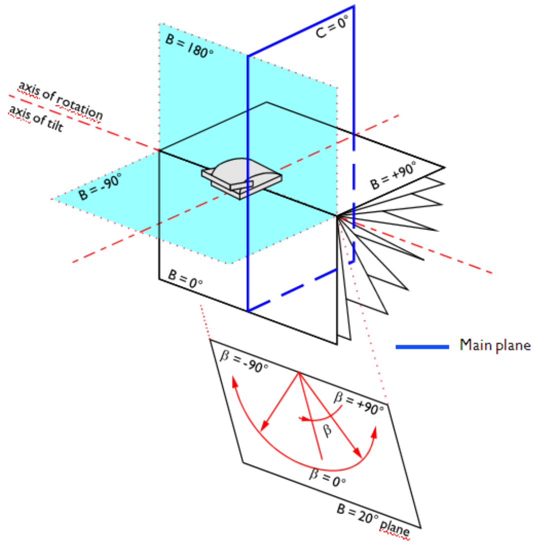



Fig. 15.19 The B-β system of coordinates used for representing the light distribution of a floodlight luminaire.

In the B-β system, which is the system used for floodlights, the axis of intersection of the B-planes corresponds to the axis of rotation of the floodlight (Fig. 15.19). The position of a particular B-plane is defined by the angle B (00 to 1800) between it and the B = 00 reference plane. The reference plane (B = 0°) is perpendicular to the front glass of the floodlight. Angle B can be positive or negative. There is a second reference plane, perpendicular to the

31 For road-lighting luminaires this C = 00 reference plane is the C-plane parallel to the longitudinal axis of the road.

floodlight's axis of rotation and passing through the centre of the unit. This is called the "main plane". A direction in a particular B-plane is indicated by the angle Beta (β), while a direction in the main plane is indicated by the angle B. With this system of coordinates it is possible to define the luminous intensity distribution of a given floodlight in the main plane over a range of B angles, or in any B-plane over a range of Beta angles.

### 15.2.2 Polar intensity diagram

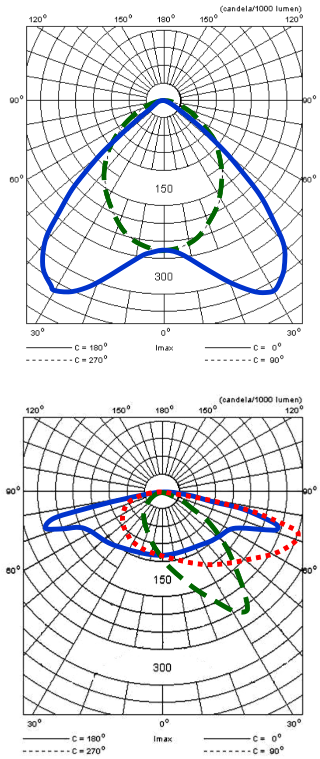



Fig. 15.20 The polar luminous intensity diagram. Left: indoor-lighting "TL" luminaire, right: road-lighting luminaire. Blue curve: C 0° - 180° plane, green curve: C 90° - 270° plane, red curve: C plane through direction of maximum intensity.

The polar luminous intensity diagram (Fig. 15.20) provides a good indication of the shape of the light distribution of a luminaire. In this diagram, the luminous intensity is presented in the form of curves and given in cd /1000 lm of the nominal lamp flux of the lamps employed. Each curve represents one C plane. Curves are given for only the more important planes. Where the light distribution of the luminaire is rotationally symmetrical, which is the case for many downlights, projectors and industrial high-bay luminaires, only one curve (for one C plane) is indicated in the diagram. This is because all other C planes have the same luminous intensity distribution. When the light distribution is not symmetrical, more curves are indicated.

In Fig.15.20 (left) an example of a common "TL" luminaire intensity distribution is given. The continuous blue line is the intensity distribution in a plane across the luminaire. The dotted green line is the intensity distribution in a plane through the length of the luminaire.

Fig. 15.20 (right) is an example of a road-lighting luminaire intensity distribution. That the light distribution across the luminaire is asymmetrical is easily noticeable from the green curve: more light is radiated towards the road rather than along the kerbside (see also Fig. 15.21). For road-lighting luminaires, the light distribution curve through the C plane where the maximum intensity is radiated is also usually shown (red curve).

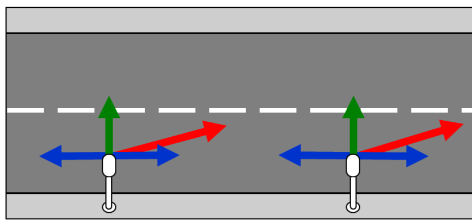


Fig. 15.21 Planes for which luminous intensity curves are given for road-lighting luminaires (red is direction of maximum intensity).

### 15.2.3 Beam spread

For well-defined beams as obtained from spotlights, downlights and floodlights, the term beam spread or beam width is used to distinguish one type of beam from another. Beam spread is defined as the angle, in a plane through the beam axis, over which the luminous intensity drops to 50 per cent of its peak value (Fig. 15.22). To provide extra information on the beam characteristics, the beam spread for another percentage (for example 10 per cent) is sometimes stated as well. Care needs to be taken with axially symmetric luminaires that the beam spread figure refers to the total angle. Some literature gives beam spread as the angle from the axis. As an example, the polar curve below would normally be described as a 60 degree beam but sometimes as 30 degree or 2 x 30 degree.

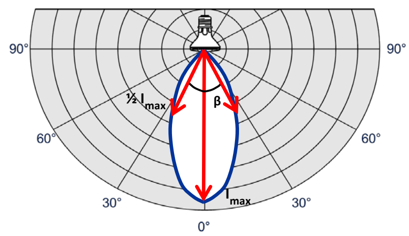



Fig. 15.22 Beam spread defined by angle β on basis of ½ Imax (50 per cent of peak intensity).

The terms “narrow beam”, “medium beam” and “wide beam” are frequently used to describe the beam spread (in the plane of interest) of a luminaire. An often-used, but by no means generally accepted, definition of these terms is that based on 50 per cent of the peak-intensity beam-spread value (Fig. 15.23):

narrow beam: < 20°

medium beam: 20° to 40°

wide beam: > 40°

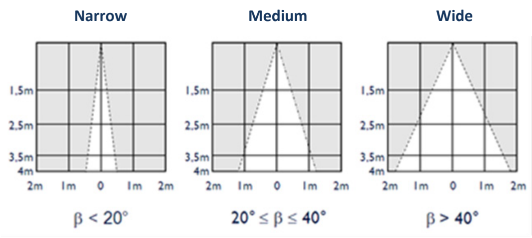



Fig. 15.23 Classification of different beam spreads based on ½ Imax.

## 15.2.4 Light output ratio

The optical devices that shape the light distribution of a luminaire absorb light. This is the reason why the total lumen output of the luminaire is lower than the lumen output of the lamp (or lamps) inside the luminaire. The light output ratio (η) is the ratio of the total lumen output of the luminaire to the lumen output of the lamp(s):

$\eta = \varphi$ luminaire / $\varphi$ lamp

The light output ratio of a luminaire is also, somewhat misleadingly, called “luminaire efficiency”. A truly efficient luminaire is one that has a light distribution that brings the light of the lamp efficiently to the spot or area where it is needed. For example, a bare-lamp luminaire with just a lamp holder and no optics has a very high light output ratio and thus very high “luminaire efficiency”, but is very inefficient in bringing the light to a particular area because it radiates light in all directions. A luminaire with suitable optics and thus a lower light output ratio can easily bring more of its light to the area required.

## 15.3 Mechanical characteristics

The mechanical function of the luminaire housing is threefold: it accommodates the various component parts of the luminaire, such as the optical system and the various components of the electrical system; protects these against external influences; and provides the means of mounting the luminaire in the installation.

## 15.3.1 Material

### Sheet steel

Sheet steel is generally chosen for the manufacture of tubular fluorescent luminaire housings for use indoors. The pre-painted sheet steel from the roll is white with diffuse reflection properties (Fig. 15.24). Thus, after having been shaped in the luminaire factory into the desired luminaire form, no finishing-off operations are required.

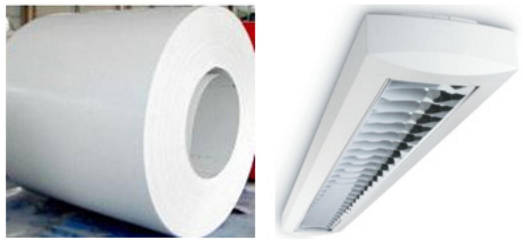


Fig. 15.24 Pre-painted sheet steel from the roll, with a luminaire housing produced from it.

### Stainless steel

Stainless steel is widely used for many of the small luminaire components, such as clips, hinges, mounting brackets, nuts and bolts, that have to remain corrosion free (Fig. 15.25).

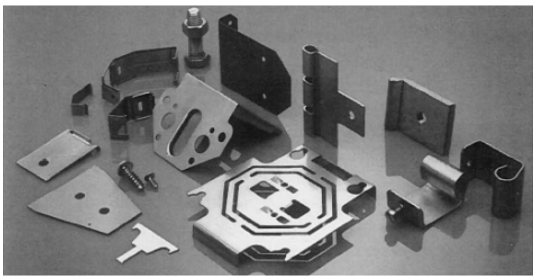


Fig. 15.25 Stainless steel luminaire components.

### Aluminium alloys

Aluminium alloys, in which other elements have been added to the pure aluminium to improve their mechanical, physical and chemical protective properties, are used to manufacture cast, extruded and sheet-metal luminaires (Fig. 15.26).[32] Cast aluminium refers to the process in which molten aluminium alloy is poured (cast) in a mould. Extrusion is the process in which softened aluminium alloy is pressed through the openings of a die. Cast and extruded aluminium alloys are much used in housings for floodlight, road, and tunnel-lighting luminaires because they can be employed in humid and damp atmospheres without having to add protective finishes.

Fig. 15.26 Aluminium-alloy luminaire housings: (left) pressed, (middle) cast, and (right) extruded.

Sheet aluminium is chiefly employed in luminaires for reflectors (Fig. 15.27). The reflectors are anodized to improve their reflection properties and to protect them from becoming matt.

Fig. 15.27 Mirror reflector of sheet aluminium protected by a plastic film, which must be removed before use.

## Plastics

Plastics are used for complete luminaire housings, for transparent or translucent luminaire covers, and for many smaller component parts (Fig. 15.28). All-plastic houses can of course only be employed for light sources that have a relatively low operating temperature.

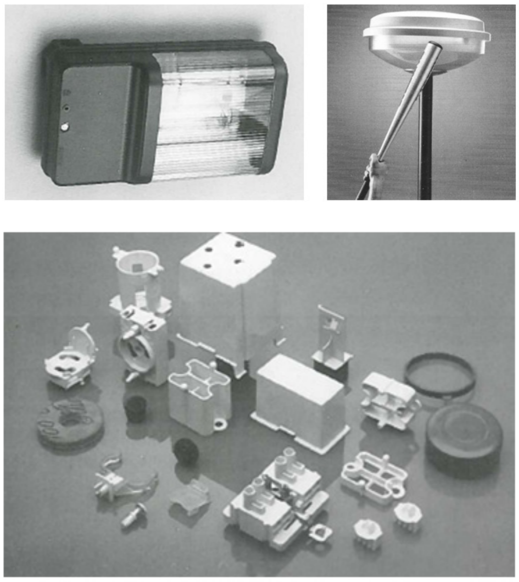


Fig.15.28 All-plastic luminaire (top left), plastic translucent luminaire cover (top right) and a selection of plastic luminaire parts (bottom).

Plastic covers are of methacrylate or polycarbonate. Methacrylate maintains its high light transmission properties over a long period, but its impact resistance is relatively low. The impact resistance of polycarbonates is very high and thus offers a high degree of protection against vandalism. It can be chemically treated to protect it from yellowing under the influence of ultraviolet radiation.

## Glass

Although glass is heavy, glass covers are used where these have to be positioned close to a light source having a high operating temperature. This is the case, for example, with HID flat-cover road-lighting luminaires and with most floodlighting luminaires. Two sorts of glass are used:

- normal glass, where no special demands are placed on heat resistance
- hard glass, where heat resistance, chemical stability and resistance to shock are important. Should hard glass break, it will disintegrate into small pieces.

Luminaires made completely out of glass are extremely heavy, and nowadays are seldom employed.

## Ceramics

Ceramic material is used in compact housings that are exposed to very high temperatures (Fig. 15.29).

32 Cast aluminium refers to the process in which molten aluminium alloy is poured (cast) in a mould. Extrusion is the process in which softened aluminium alloy is pressed through the openings of a die.

Fig. 15.29 Ceramic compact spots

## 15.3.2 Strength

All luminaires should have housings of sufficient rigidity to withstand normal handling, installation and use. With indoor-lighting luminaires for fluorescent lamps, stiffness and rigidity of construction is particularly important, since these lamps are relatively large and awkward to handle. Perhaps the most critical part of a luminaire as far as strength is concerned are the mounting brackets. The strength required here is covered by a safety factor: the mounting bracket(s) must be able to support at least five times the weight of the luminaire itself. With road-lighting and outdoor floodlighting luminaires, the mounting brackets must also be strong enough to withstand the highest conceivable wind loading for the location. Here a good aerodynamic shape for the luminaire can be advantageous, as it also serves to reduce the strength required for the lighting mast. The term "windage" is used to refer to the projected area of the luminaire against the wind. The smaller the windage, the lower is the resistance to the wind.

Under some circumstances, the impact resistance of the luminaire itself is also important, particularly where protection against vandalism is called for. Reference can be made in this respect to standards that specify the required impact resistance for different conditions of use. These conditions vary from being able to withstand the impact of a falling object of 200 gram from a height of 10 cm (low impact resistance), to withstanding the impact of a 5 kg object from a height of 40 cm (vandal-proof luminaires).[33]

## 15.3.3 Resistance to pollution and humidity

The atmosphere can contain many potentially-corrosive gases which, in the presence of moisture vapour, will form highly-corrosive compounds. In all areas where this danger exists (notably in outdoor applications, indoor swimming pools and certain industrial premises) luminaires made from corrosion-resistant materials or having protective finishes should be used. In such areas, the luminaire should protect the optical and electrical components it houses. It should, of course, be fully enclosed. The degree of protection provided by the luminaire is classified according to the International Protection code (IP code) as described in an international IEC standard. The IP code consists of two numerals: IP • •.

- The first numeral classifies the degree of protection against the ingress of solid foreign bodies (ranging from fingers and tools to fine dust) and protection against access to hazardous parts (Table 15.2).
- The second numeral classifies the degree of protection against the ingress of moisture (Table 15.3). The higher the IP values, the better the protection.

| First figure and symbol | | Description | Protected against |
|---|---|---|---|
| 0 | | Non-protected | -- |
| 1 | | Hand protected | solid objects exceeding 50 mm |
| 2 | | Finger protected | solid objects exceeding 12 mm |
| 3 | | Tool protected | solid objects exceeding 2.5 mm |
| 4 | | Wire protected | solid objects exceeding 1 mm |
| 5 | | Dust protected | protected against harmful accumulation of dust |
| 6 | | Dust tight | protected against penetration of dust |
| X | | Not defined | -- |

Table 15.2 IEC classification of luminaires according to the degree of protection against access to hazardous parts and the ingress of solid foreign bodies (first digit of IP code).

| Second figure and symbol | | Description | Protected against |
|---|---|---|---|
| 0 | | Non-protected | -- |
| 1 | | Drip-proof | vertical falling water drips |
| 2 | | Drip-proof | vertical falling water drips when titled at angles up to 15 |
| 3 | | Rain/spray-proof | water falling at an angle of up to 60 |
| 4 | | Splash-proof | splashing water from any direction |
| 5 | | Jet-proof | water projected by a nozzle from any direction 9nozzle 6.3mm, pressure 30 kPa) |
| 6 | | Jet-prrof | water projected by a nozzle from any direction 9nozzle 12,5mm, pressure 100 kPa) |
| 7 | | Watertight | temporary immersion in water |
| 8 | ...m | Pressure watertight | continous submersion in water |
| X | | Not defined | -- |

Table 15.3 IEC classification of lumiaires according to protection against harmful ingress of water (second digit of IP code).

Dust and watertight (or waterproof) luminaire covers must always be used in conjunction with a sealing strip in combination with a strip channel for maximum effect. Due to the variation in temperature

33 These requirements are also expressed in impact joules from a pendulum or spring hammer as used in luminaire testing laboratories. A European norm classifies luminaires according to the test result in IK classes ranging from IK00 to IK10 (vandal-resistant).

between the air inside and that outside the luminaire after switching on or off, pressure differences across the luminaire's cover-seal are bound to occur. This effect is referred to as "luminaire breathing". The seal should prevent corrosive gases, moisture and dust from being sucked into the luminaire during cooling off. The effectiveness with which the front cover seals the luminaire against ingress of solids and liquids, and the durability of this sealing function, is determined by the type and quality of the sealing material employed. Typical examples of environments requiring IP 20, IP 54 and IP 65 protection respectively, are shown in Fig. 15.30.

Fig. 15.30 Environments requiring (from left to right) luminaires with IP code 20, 54 and 65 respectively.

### 15.3.4 Ease of installation and maintenance

Many luminaires are of such a shape, size and weight as to make mounting them a difficult and time-consuming operation. Mounting, but also relamping and cleaning, must usually be carried out high above ground level. So the ergonomic design of the luminaire should be such as to make these operations as easy and as safe as possible to perform. For example, covers should be hinged so that the electrician has his hands free to work on the lamp and gear. A good, ergonomically designed luminaire is one that can be mounted in stages: first the empty housing or a simple mounting plate, which is light and easily handled, then the remaining parts.

## 15.4 Electrical characteristics

The electrical function of a luminaire is to provide the correct voltage and current for the proper functioning of the lamp in such a way as to ensure the electrical safety of the luminaire.

### 15.4.1 Lamp holders

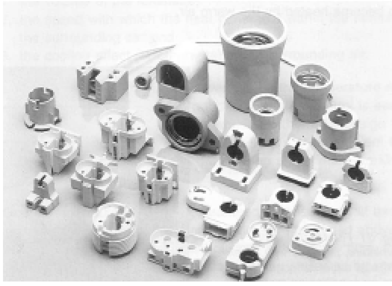


Fig. 15.31 A variety of lamp holders made of both plastics and porcelain.

The most usual types of holder are the Edison screw, the bayonet and the pin (Fig.5.31). Most Edison screw and bayonet holders are made of plastics or porcelain, with metal parts for carrying the current. Porcelain is resistant to high temperatures and has a high voltage-breakdown resistance, which is important considering the high ignition voltage of HID lamps. The pin lamp holders for tubular fluorescent and compact fluorescent lamps are nearly always made of plastic. The metal contacts are spring loaded to ensure a constant contact pressure.

### 15.4.2 Electrical wiring

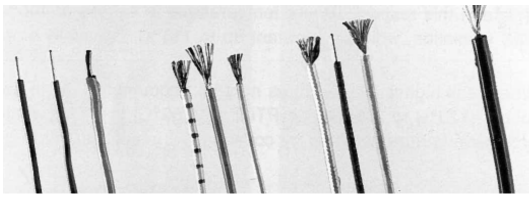


Fig. 15.32 Different types of electrical wiring used in luminaires. From left to right: solid core (3), stranded (3), stranded with heat-resistant insulation (3), and high-voltage ignition cable (1).

The electrical wiring in a luminaire must be such as to ensure electrical safety. This necessitates great care in the choice of wire used and its installation. There are a great many different types of wire available, in both single-core (solid) and multi-core (stranded) versions (Fig. 15.32), all with various cross-sectional areas and clad with various thicknesses and qualities of insulation.

Single-core wire is much stiffer than stranded wire, which means that fewer cable fasteners are needed to hold it in position. It is also easier to strip and is more suitable than stranded wire for the internal wiring of a luminaire. However, single-core wire is not suitable for use in luminaires that are subject to vibration and shock. In such cases a stranded wire must be used.

The cross-sectional area (thickness) of the wire must be matched to the strength of the current flowing through it.

The insulation of the wire used must be resistant to the high air temperature in the luminaire and the temperatures of the luminaire materials with which it is in direct contact. This is true not only under normal conditions of operation, but also in the presence of a fault condition.

### 15.4.3 Mains connection

The method used to connect a luminaire to the power supply must be both quick and safe. The practice generally adopted is to incorporate a connection block in the housing, although prewired luminaires in which the electrical connection to the mains is automatically made when the unit is placed in position are also available.

### 15.4.4 Electrical safety classification

The electrical safety classification drawn up by the IEC embraces four luminaire classes (Table 15.4).

| Safety class | Symbol | Protection |
|---|---|---|
| 0 | □ | Basic insulation only |
| I | ⏚ | Basic insulation plus protective earth connector |
| II | ⧈ | Double or reinforced insulation, no provision for protective earthing |
| III | ◇ III | Supply of safety extra-low voltage |

Table 15.4 IEC electrical safety classes.

- Class 0: Applicable to ordinary luminaires only. These are luminaires having functional insulation, but not double or reinforced insulation throughout and with no provision for earthing.
- Class I: Luminaires in this class, besides being electrically insulated, are also provided with an earthing point connecting all those exposed metal parts that could become live in the presence of a fault condition.
- Class II: This class embraces luminaires that are so designed and constructed that exposed metal parts cannot become live. This can be achieved by means of either reinforced or double insulation. They have no provision for earthing.
- Class III: Luminaires in this class are those designed for connection to extra-low-voltage circuits (smaller than 50 VRMS, referred to as Safety Extra-Low Voltage, SELV). They have no provision for earthing.

Fig. 15.33 shows examples of luminaires of these four classes.

Fig. 15.33 From left to right, examples of luminaires of IEC electrical protection class 0, I, II, and III respectively.

## 15.5 Thermal characteristics

### 15.5.1 Temperature control

A considerable amount of the electrical energy supplied to the lamp is converted into heat. The ballast adds to this heating effect within the luminaire. To protect the ballast from overheating, it is sometimes, especially with high-power lamps, screened off from the heat radiation of the lamp and placed in a separate compartment of the luminaire. With very-high-powered lamps, it should be placed outside the luminaire in a special ballast box.

For a given lamp/ballast combination, the working temperature reached by the luminaire is dependent upon three factors:

- The volume of the luminaire. The greater the volume, the lower will be the temperature rise inside the luminaire.
- The ease with which the heat generated within the luminaire can be conducted through it to the surrounding air. One way of promoting air flow through the housing is to make use of heat-conducting materials in its construction. Most metals are good in this respect, while plastics, on the other hand, are thermal insulators and cannot therefore be employed as housing materials where high-power lamps are involved.
- The cooling effect of the surrounding air. Good heat dissipation calls for large surface areas to be in contact with the surrounding air. Luminaires for high-power lamps, such as high-bay luminaires, floodlights, and some LED luminaires, that are very sensitive to high temperatures, are therefore provided with cooling fins (Fig. 15.34). Some types of industrial luminaires are provided with air vents in the top of the housing to allow the warm air to escape.

Fig. 15.34 Metal halide high-bay luminaire (left) and recessed LED downlight with cooling fins (shown in side view and when recessed in the ceiling) .

Luminaires are designed to meet the conditions under which they are most likely to be used. The maximum ambient temperature, Ta, at which a luminaire can be operated safely, is indicated on the type label on the product. If no temperature indication is given, the product is intended for use at a maximum ambient temperature of 25°C, which is the case for the majority of luminaires designed for indoor applications. The use of luminaires above their specified maximum ambient temperature may reduce safety margins and will generally lead to a reduction of the lifetime of the various luminaire components. Luminaires designed for industrial applications have higher ambient-temperature limits, as high as 40°C to 45°C, and in special cases even higher. Many manufacturers offer for example products suitable for 50°C which is often a requirement in the Middle East markets.

### 15.5.2 Protection against flammability

#### Luminaire flammability

The flammability of a luminaire operating under fault conditions is an issue with luminaires made of plastics. As an example: acrylic is superb optically, but a real fire hazard in large sheets. The combustion behaviour of luminaires is not just material dependent, it also depends on the shape and thickness of the luminaire housing. The IEC has defined a so-called glow-wire test that assesses the fire hazard at different glow-wire temperatures (Table 15.5).

| Symbol | passes glow wire test at |
|---|---|
| 550ºC | 550 ºC |
| 650ºC | 650 ºC |
| 750ºC | 750 ºC |
| 850ºC | 850 ºC |
| 950ºC | 950 ºC |

Table 15.5 IEC fire-hazard classes.

#### Flammability of mounting surface

Luminaires cannot simply be mounted on any type of surface – there is the degree of fire risk to be considered. This is determined by the combination of surface flammability and the temperature of the luminaire mounting plate.

Whilst it is always safe to mount luminaires on non-flammable building materials such as concrete and stone, other surface materials impose certain limitations as specified in the IEC protection classes (Table 15.6). Luminaires for discharge lamps bearing an F-sign are also suitable for mounting on building surfaces that do not ignite below 200°C, while luminaires for discharge lamps bearing an FF-sign have a lower surface temperature and so can even be mounted on easily-flammable surfaces (Table 15.6). Most Philips indoor luminaires for surface mounting are of the F class. In very dusty environments where dust collected on top of the luminaire might ignite in the event of a fault, FF classified luminaires are required.

| Symbol | Application | Remarks |
|---|---|---|
| ---- | Suitable for mounting on non-flammable surfaces | Stone or concrete |
| F | Suitable for mounting on normally normally flammable surfaces | Ignition temperature of materials > 200 ºC |
| F F | Suitable for mounting on easily flammable surfaces | Ignition temperature of materials < 200 ºC |

Table 15.6 IEC protection classes of luminaires with regard to the flammability of the mounting surface.

## 15.6 Aesthetics

No less important than the functional characteristics of a luminaire is what is termed its aesthetic or visual appeal, that is to say its appearance and styling. In interiors, all non-recessed luminaires are clearly visible, and so whether switched on or not their design should be in harmony with that of the interior. In outdoor lighting, it is usually only the daytime appearance of the luminaires, when these are clearly visible, that is important: particularly in built-up areas, their design can make a positive contribution to the attractiveness of the locality.

## 15.7 Indoor luminaires

### 15.7.1 General lighting

The term general lighting is used to denote the substantially uniform, functional lighting of a space without provision for special local requirements. Often, but not always, the general lighting is supplemented with accent or task lighting. General-lighting luminaires can be divided according to their light distribution into direct, indirect and direct-indirect types (Fig. 15.35). The direct-indirect types are available with differing upward and downward components. If the downward component is clearly larger than the upward component, the term semi-direct is used, while the versions where the upward component is the larger are referred to as being semi-indirect luminaires.

Fig. 15. 35 From left to right: direct, indirect and direct-indirect types of luminaires.

**Recessed luminaires**

Ceiling-recessed luminaires are mostly of the direct type, although a small upward component (semi-direct) can be obtained if the light-emitting surface is not flush with the ceiling and specific optics are employed (Fig. 15.36). There are luminaires for various types of modular and non-modular ceiling systems. Certain types of recessed luminaires may be employed as air-handling luminaires.

Fig. 15.36 Recessed luminaires with a direct (top) and semi-direct (bottom) light distribution.

**Surface-mounted luminaires**

Surface-mounted luminaires are also normally of the direct type, but semi-indirect versions can be produced as well. Many general lighting luminaires of the same type are available in both recessed and surface-mounting versions, sometimes also in a version for suspended mounting.

Fig. 15.37 Surface-mounted luminaires: for LED (left) and for TL.

**Suspended luminaires**

Suspended luminaires are available in a wide range of direct, semi-direct and semi-indirect versions. The use of suspended luminaires facilitates localisation of the general lighting, whereby some of the general lighting is concentrated on actual work places. Whilst the shape of a recessed luminaire is hidden in the ceiling, that of a suspended luminaire is clearly visible. Its design appearance therefore becomes much more important (Fig. 15.38).

Fig. 15.38 With suspended luminaires, both the light characteristics and the design appearance are important.

**Free-standing luminaires**

For localised general lighting or for additional work-space lighting, free-standing luminaires can offer a flexible solution (Fig. 15.39). Efficient versions make use of tubular fluorescent, compact fluorescent and LED light sources.

Fig. 15. 39 Free-standing luminaires.

## 15.7.2 Accent lighting

### Projectors

Fig. 15.40 Examples of surface-mounted and rail-mounted projectors for LED (left) and compact CDM.

Projectors or spotlights (Fig. 15.40) are directional-lighting luminaires that are used mainly to provide accent lighting. The projector obtains its directional light control in one of three ways: from the lamp itself, with its built-in reflector; from an external reflector built-into the luminaire; or from a combination of these two. Depending on the system employed, the beam spread varies from wide and medium to narrow. Most projectors have a joint construction so that the direction of the beam can easily be adjusted. Multiple projectors mounted in a single frame permit of a multiplicity of beam directions from one location (Fig. 15.41).

Projectors make use of compact metal halide, white SON, halogen and, more and more, LED light sources.

Fig. 15.41 Multi-projector, frame-mounted lighting system.

### Downlights

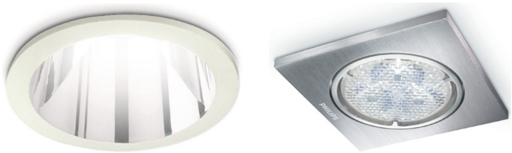


Fig. 15.42 Examples of recessed downlights: left, compact fluorescent and right, LED.

Downlights (Fig.15.42) are, in effect, spotlights recessed into, mounted on, or suspended from the ceiling. They are used not so much for the lighting of objects but for providing additional, concentrated light on certain areas of a space. They therefore usually have a medium or wide beam spread.

### Wall washers

Wall washers are used where a relatively large area has to be uniformly lighted. School blackboards and display shelves in shops are examples of where wall washers might be employed for functional reasons. But wall washing also has an aesthetic or visual appeal. The luminaires are ceiling or wall mounted (recessed, surface mounted or suspended) and have the appropriate asymmetrical light distributions.

### Markers

The small size of LEDs makes them extremely suitable for recessed or surface-mounted wall and floor markers. Besides their functional use in marking locations in space and guiding people through space, they can also create stunning 'light art' and light accents (Fig. 15.43).

Fig. 15.43 Example of wall and floor markers (LED).

## 15.7.3 Industrial lighting

### Batten luminaires

Batten luminaires are basic linear fluorescent or LED luminaires specifically designed for ease of mounting (Fig. 15.44). Mounting is mostly surface or cable suspended. They come in a variety of IP classes (up to waterproof IP 66 or 67) to suit many different industrial conditions. Separate accessories that can easy be mounted to the basic luminaire, include reflectors, diffusers and louvres for lamp screening.

Fig. 15.44 Batten luminaires: with tubular fluorescent lamps and simple reflector, and with LEDs.

### Light lines

Fig. 15.45 An example of a light-line system.

Light-lines make use of a trunking (support) system to which lines of batten-type of luminaires specifically designed for that trunking system can be quickly and easily mounted (Fig. 15.45). The trunking system consists of a strong rail that has two functions: it carries the luminaires and gear and it houses the electrical wiring for the supply of power (and, where relevant, for controlling different switching or dimming steps). The trunking system itself can be either surface mounted or suspended. The trunking sections are electrically joined together by coupling connectors that do not call for the use of tools (Fig. 15.46). After the trunking system is installed the luminaires are simply clicked onto the trunking system (Fig. 15.47). Spotlights with a special adapter can also be clicked onto the trunking system.

Fig. 15.46 The components of a trunking system: the catenary adapter (left), the trunking section (middle), and the cable track that is incorporated in the trunking section (right).

Fig. 15.47 Luminaires mounted on the trunking system.

### High and low-bay luminaires

Mounting heights above approximately five metres call for the use of luminaires housing powerful HID lamps. With these high-intensity lamps good glare control calls for high-precision optics. Depending on the mounting height, narrow-beam, medium-beam or wide-beam light distributions are needed. In many rotationally-symmetrical low and high-bay luminaires such distributions can be obtained by moving the lamp up or down in the reflector Many of these luminaires are of the suspended type, with built-in electrical gear (Fig. 15.48).

Fig. 15.48 High or low-bay HID luminaire.

TThese luminaires can be rather heavy and awkward to handle, and yet must often be mounted high up in industrial halls. They are therefore often designed as two easily-assembled parts: the lamp housing with its control gear including electrical wiring, and the reflector. Once the former is mechanically fixed in position and connected to the supply, a suitable reflector is simply clipped into position. Especially in industrial areas, the luminaires are equipped with a hard-glass cover. Depending on the intended application, these luminaires have either a relatively low IP class (non-industrial areas with high ceilings) or a high IP class of up to 65 (dusty and humid industrial areas).

## 15.8 Outdoor luminaires

Outdoor lighting installations are designed to provide traffic safety (road lighting, tunnel lighting and urban lighting), personal security (urban lighting), a pleasant and inviting night-time environment (urban lighting and architectural outdoor lighting), and the possibility to work and play outdoors after dark (sports and area lighting).

### 15.8.1 Road lighting

Luminaires for road lighting with the focus on traffic safety are either mast, wall or suspension (span-wire) mounted. Their light distribution is such that the main vertical plane of symmetry lies at right angles to the longitudinal axis of the road, thus throwing the main part of their light along the road. Where in the past both reflectors and large refractors were used to create that light distribution, today most road-lighting luminaires make use of reflectors or, in the case of LED luminaires, also refractor lenses. Mast-mounted road-lighting luminaires make use of two different mounting systems: bottom entry (post top) or side-entry sockets (Fig. 15.49). The side-entry versions are also used for wall mounting. Span-wire, or catenary, luminaires are suspended from a cable by means of brackets on their topside. The strength of the mounting sockets or brackets of road-lighting luminaires is important because these luminaires can be buffeted by strong winds. The aerodynamic shape of the luminaire plays an important role in this respect as well. Not only must the bracket be strong enough to withstand the highest wind loading, it must also be rigid enough to prevent vibration of the housing, as this can lead to premature lamp failure and fracture of the support bracket.

Fig. 15.49 Side-entry and post-top mounting. Note the screens on the luminaire on the right.

Often the luminaire has a separate compartment for the electrical control gear (Fig. 15.50), but sometimes the gear is located in the bottom of the mast.

Fig. 15.50 Luminaires with separate compartments for the control gear (driver) and for the lamp/reflector. Left: HID luminaire, right: LED luminaire (note the cooling fins of the LED lamp unit)

### 15.8.2 Urban lighting

The lighting installation in an urban environment should enhance the safety and security of motorists, cyclists and pedestrians, but it must also be pleasing and inviting as well. In addition to the road-lighting luminaires described in the previous section, in urban areas we therefore see an ever-increasing number of luminaires with a design that helps to give the area its own pleasing identity. The relatively large freedom of luminaire design when using small LED units is much appreciated in this respect. At the relatively-low mast heights used in urban areas (3 m to 8 m), the daytime appearance of the mast-luminaire combination is very important. Masts, mounting brackets and luminaires in many different styles are employed, including customized designs. Sometimes masts and luminaires are completely integrated into one product: true light columns (Fig. 15.51).

Fig. 15.51 Mast-luminaire combinations as a single product.

The light distribution of urban lighting luminaires on long stretches of road has to be similar to that of "normal" road-lighting luminaires (casting the main part of their light along the road). On shorter stretches, and in squares, plazas and courts, a more rotationally-symmetrical light distribution is used.

### 15.8.3 Architectural floodlighting

In addition to what has been described in the previous section, the architectural highlighting of urban landmarks is another powerful tool used to give identity to an urban environment. Relatively small spotlights and floodlights based on LEDs can, because of their small light-emitting surface, give very narrow, near-parallel light beams (Fig. 15.52). This makes them particularly suitable for the lighting of landmarks in an unobtrusive way. The luminaires are also produced with wider beams. Fig. 15.53 shows some examples of LED floodlights for architectural outdoor lighting. Many of these luminaires are available in both white and coloured-light versions, the latter also with dynamic, colour-changing possibilities.

Fig. 15.52 Near-parallel light beam with a LEDline luminaire.

Fig. 15.53 Examples of LED floodlights for architectural outdoor lighting. Left: narrow-beam LEDline; middle: colour-variable floodlight; right: surface-mounted and recessed floodlights. All with possibility for dynamic colour changing.

High-power floodlights making use of both compact and normal HID lamps are employed for architectural outdoor lighting as well. Fig. 15.54 shows some examples.

Fig. 15.54 Examples of HID floodlights for architectural outdoor lighting.

### 15.8.4 Tunnel lighting

Tunnel lighting luminaires are either wall or ceiling mounted. Because of the limited space in tunnels, the height of the luminaire is especially critical. The tunnel interior is always lighted by luminaires having a symmetrical light distribution relative to the axis of the tunnel. The tunnel entrance, where very high daytime lighting levels are required, can be lit with luminaires having a transverse symmetrical (the main beam is directed across the tunnel), an axial symmetrical, or an asymmetrical counter-beam (aimed towards oncoming traffic) light distribution (Fig. 15.55).

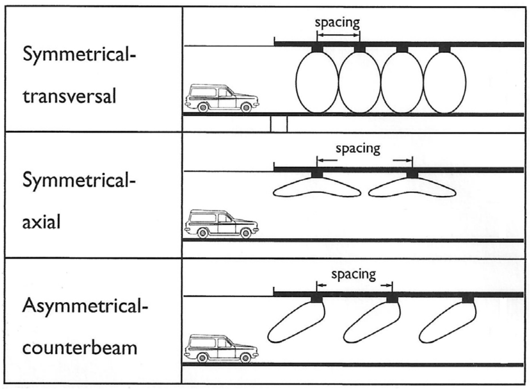



Fig. 15.55 Different types of light distribution for tunnel-lighting luminaires.

Whatever type of light distribution is chosen, it has to be fine-tuned for the actual tunnel width and tunnel height in question. Modular luminaire designs that allow for flexibility in lamp and optics combinations in one and the same housing are therefore essential (Fig. 15.56).

Fig. 15.56 Examples of a modular tunnel-lighting luminaire concept.

### 15.8.5 Sports and area lighting

Floodlights for sports and area lighting make use of all the different types of high-intensity HID lamps up to a power of 2000 W. LED floodlights are available as multi-LED units for the intermediate intensity versions. The mounting height of the floodlights varies from some 10 m for the somewhat lower-powered units to more than 40 m for the high-power units. Ease of mounting is essential where the higher mounting heights are concerned. Three basic types of light distribution are employed: rotationally symmetrical (circular or ellipsoidal light pattern); symmetrical about two perpendicular planes (rectangular light pattern); and asymmetrical. It is often wrongly thought that all rotationally-symmetrical floodlights have a rotationally-symmetrical light distribution, whereas very often they have in fact an asymmetrical distribution. This is either because of the asymmetrical reflector shape or because of a built-in reflective screen to prevent glare (Fig. 15.57).

Fig. 15.57 Examples of floodlight light distributions. Top left: asymmetrical light distribution (floodlight with support for removable aiming telescope); top right: plane symmetrical light distribution about two planes; bottom: LED floodlight with asymmetrical light distribution.

Most floodlight types are available in wide, medium-beam and narrow-beam versions. (The latter in case of asymmetrical beams in one of the main planes). Since a floodlight must be aimed once it is secured in position, it is equipped with a sturdy mounting bracket that allows the unit to be rotated in the two vertical and horizontal planes. Many floodlights are equipped with a simple gun-sight aiming device or, where more accurate or complex aiming is required, a support for mounting a telescopic sight (Fig. 15.57).

### 15.9 Approval

Luminaires always have to comply with the appropriate safety rules. ENEC (European Norms Electrical Certification) is the European mark for demonstrating compliance with all European Safety Standards. UL (Underwriters' Laboratories) is the similar USA mark (Fig. 15.58). Both certification institutes know both prototype testing and testing of the production process.

Fig. 15.58 ENEC and UL certification marks. The number in the ENEC mark indicates the country of the institute that has given the European approval.

# 16 Lighting Controls

Lighting control systems can minimize the energy consumption and maintenance costs and maximize the life of lighting installations. They can improve the performance and comfort of users by continuously providing the correct lighting for the task in hand and the visual capability of the worker which, amongst other things, is age dependent. Lighting control and monitoring systems can automate the management of lighting installations to a great extent, thus further increasing the cost effectiveness of the installation.

## 16.1 Basics

The most simple example of lighting control is the switching on and off a luminaire with a simple switch that is connected between the mains supply and the luminaire. The most advanced control system is a set of input devices such as switches, photocells, timers, occupancy detectors (or, for road lighting, traffic-flow detectors) that together are centrally programmed to control, without wires, the lighting status of a large number of individual or grouped luminaires (scene setting). One step further brings us to truly-intelligent lighting control and monitoring systems. Here, not only is information on the required lighting status sent to the luminaires, but the operational state of the luminaires themselves (e.g. lifetime of the lamps, actual lamp voltages, lumen output and colour of the lamps) is sent back to a central location for evaluation, inspection and administrative purposes (telemanagement).

Basically, each lighting control system consists of:

- input devices: such as switches, timers, photocells, occupancy detectors, traffic-flow detectors, and weather monitors
- controlled luminaires: that can be switched, or dimmed, or colour changed or aimed (or combinations of these). In a programmable control system they should be (hardware or software) addressable
- the control system itself
- control network: the link between the input devices and the luminaires being controlled and (in the case of controlled systems) with programmable controllers.

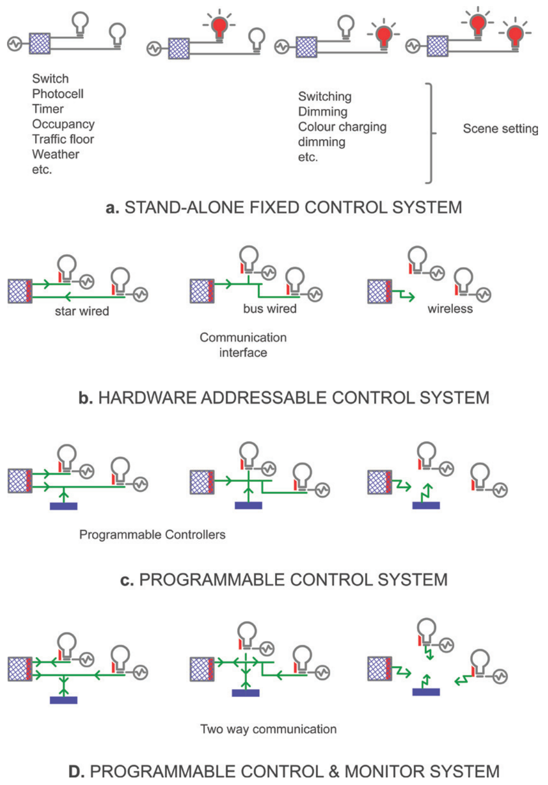



Fig. 16.1a shows a scheme of a simple stand-alone, fixed-wired, two-luminaire control system, connected direct to the mains. Fig. 16.1b shows a (hardware) addressable lighting control system where the mains-voltage network is separated from the control network. The control network may consist of a star-wired, bus-wired or wireless system, or a combination of wired and wireless systems. The wires of the control network can be much simpler than those of the mains wires. The wireless system may be IR or wifi or a combination of the two. Both the input devices and the controllable luminaires have a hardware-addressable interface employing, for example, dip or rotary switches.

To send messages to the controlled luminaires a digital communication protocol is used. This is a system of digital message formats in the form of modulated electric current, modulated IR radiation, or wifi signals. Fig. 16.1c shows a programmable control system. A programmable controller is connected to the system, so that the lighting system can be centrally controlled and adapted to changing needs without touching the hardware of the installation. The interface can be temporarily connected to a PC at the moment changes have to be put into the system, or continuously connected if frequent adaptations are being made. Standardized digital communication protocols have been defined that facilitate the interchangeability of components, sometimes also between components of different manufacturers. Popular protocols used for lighting are DALI, DMX and LonWorks (see later sections). Finally, Fig. 16.1d illustrates a programmable two-way communication system which is, in fact, a control and monitor system.

## 16.2 Input devices

Input devices, or sensors, react to signals from one or more of the following: human inputs (switches), time (timers), light level (photocells), occupancy (occupancy detectors), traffic conditions (traffic flow, driving speed and road-surface condition detectors) and weather (rain, snow and fog detectors and/or visibility range detectors). If used in an addressable, automated control system they need an interface that is able to communicate (send) both its address and the detected signal to the system. This communication interface is usually an integral part of the input device.

### 16.2.1 Switches

Most modern lighting control systems make use of remote, IR-controlled switches. The control possibilities (Fig. 16.2) vary from simple on-and-off switching to dimming or white-light control (cool/warm) or full colour control. Some devices have pre-set buttons that allow certain lighting scenes to be stored.

Fig. 16.2 Examples of remote-control switches. Top: wall-mounted and hand-held switching-only devices. Bottom left: switching and dimming with pre-sets. Bottom right: full-colour changing and dimming device.

### 16.2.2 Timers

There is a large variety of simple mechanical and electronic timer switches on the market that turn luminaires on and off at pre-set times. Most advanced lighting-control systems have timers built in so that time programmes can be integrated in the total control of the installation. Timers are particularly important in road-lighting control systems. Here the timer sets the moment when the lighting is switched on and off throughout the year according to the changing times of dusk and dawn, respectively.

### 16.2.3 Photocells

Photocells (Fig. 16.3), either built into the luminaire (stand-alone system) or remotely connected to the lighting control network, are used for two reasons:

- to control the artificial lighting according to the amount of daylight available
- to ensure a lighting level that is according to specification during the whole period of operation of the installation

Advanced photocells have the possibility to define the measurement area that is covered. Some photocells are combined with an occupancy detector in one housing, and others also incorporate an IR receiver to allow the lighting to be switched using remote switches

Fig. 16.3 Examples of photocells. Left: stand-alone cell for mounting on a tubular fluorescent lamp and wired directly to the dimming ballast. Right: Multimeter with photocell, occupancy detector (in the centre of the device) and IR receiver.

### 16.2.4 Occupancy detectors

An occupancy detector is a motion sensor that is integrated with a timing device. It senses when movement in the interior being lighted has ceased for a specified period of time, and then signals the lighting to be set to a predetermined lower level or to be switched off entirely. If, on the other hand, the sensor detects even a slight amount of movement, the lighting remains on or is set at a pre-set lighting level. The motion sensors employed in normal lighting control systems usually make use of passive infrared. Passive, in that the sensor does not radiate infrared but measures changes in the infrared radiation from its surroundings.

Like advanced photocells, advanced occupancy detectors have the possibility to define the measurement area that is covered. They may also have the possibility to introduce a time delay before the lighting is reduced or switched off once no movement has been detected (delayed switch-off time). This can be incorporated in hardware (dip switch) or in the software execution.

Fig. 16.4 Examples of occupancy detectors. Left: for wall mounting. Right: for recessed ceiling mounting (the small extendable cylinder around the motion sensor can be used to adjust the detection range).

### 16.2.5 Traffic-condition detectors

The information provided by traffic-condition detectors, such as speed, traffic-flow, weather conditions (dry, wet, snow, fog) and road-surface condition (wet or icy), can be the input needed by the lighting control system to arrive at demand-dependent road lighting.

## 16.3 Control systems

The control network and communication protocols used in today's lighting control systems may use one or more of the following technologies:

- Stand-alone system
- 1-10V dimming system
- DALI control system
- DMX control system
- Powerline control system
- LonWorks control system

Some systems make use of a combination of these technologies.[34]

### 16.3.1 Stand-alone system

Input devices directly wired to controlled luminaires or group of luminaires without the possibility to be programmed, form a stand-alone system that can only be changed by reconnecting input devices to other individual luminaires or groups of luminaires. Such simple systems are often used, for example, to control the light output of a row of indoor luminaires nearest to the windows in response to the amount of daylight available as monitored by a photocell. Another popular application for such systems is the automatic switching of the lighting on the basis of presence detection in rooms or corridors that are seldom used.

### 16.3.2 1-10 volt dimming system

This is one of the oldest lighting control systems used for dimming gas discharge lamps. The technique was introduced by Philips and has since been standardized by the IEC.

The control signal is a DC voltage that varies between one and ten volts. A dimming interface integrated in the luminaire ballast is used to control the luminaire's light output in response to the value of this voltage. The response can be linear or logarithmic, in the latter case it is proportional to the perceived brightness of the light. Most gas discharge lamps cannot be completely dimmed down to zero, in which case a relay should be added to the system to completely switch off the lighting.

The 1-10 volt controller has at least one connection for an input device and one connection for the luminaire being controlled (one channel). Many controllers have multiple inputs and multiple output channels (Fig. 16.5).

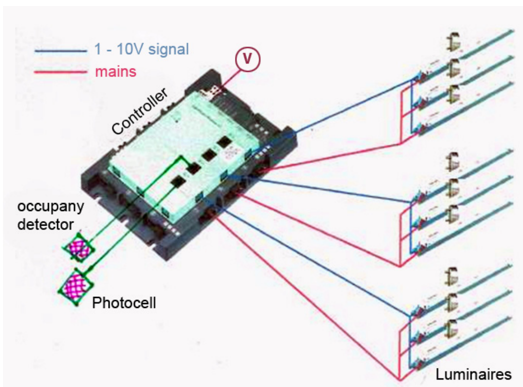



Fig. 16.5 Example of a 1-10 volt lighting controller used for dimming/switching gas discharge luminaires with four input and nine output channels

While the 1-10 volt system is technically simple and its control wires can be thin due to the low currents, it is not very suitable for larger installations because

34 Where the whole or part of the network is wireless, modulated infrared or modulated radio waves within specific frequency ranges are used as information carriers (IR control and radio frequency, RF, or wifi control respectively).

it requires separate wiring for each control channel. The control circuits must be hard-wired because the luminaires have no addresses. In complex systems many cables are therefore needed, requiring colour-coding to distinguish the various circuits. When the lighting scene as obtained with groups of luminaires has to be changed, the system has to be rewired. This is because the system is a one-way system: information is sent from the controller, but no information on the status of the system and of the luminaires is returned. The maximum permitted length of the control cables is 300 metres.

### 16.3.3 DALI

DALI is a digitally-addressable control system specifically developed for lighting control by a consortium of lighting manufacturers (AG-DALI), that includes Philips Lighting. The system is now standardized by the IEC. DALI stands for Digital Addressable Lighting Interface. Its logo is shown in Fig. 16.6.

Fig. 16.6 Logo of DALI.

The standardized system includes both the communication protocol and the electrical interface for lighting-control networks. It is an open standard, which is to say that in principle components of different manufacturers can be used in one and the same DALI system. Since DALI can send and receive information (it is a two-way system), it can be used as a lighting control and monitoring system that sends not only commands but also queries. This means that the status of the network is continuously available for inspection and administrative purposes.

The "messages" that are sent through the network include the address of the input device, the address of the luminaire being controlled, and the action required by the luminaire (based on the signal as measured by the sensor in the input device). Both the input device and the luminaire must have a DALI interface (usually integrated in the input device and the digital ballast or driver). What input device address or addresses are connected with what luminaire address or addresses (groups of luminaires) is determined by the software in the controller. The DALI luminaires can thus be controlled individually or in groups, which allows for scene setting. Of course, the setting or settings can be easily and quickly reprogrammed according to changing circumstances or wishes. The intelligence of The DALI system is not stored centrally but in its interfaces with the input devices and with those of the luminaires being controlled.

The control wires can be wired together with the mains supply line (for example, in one five-wire cable) if this serves to simplify the installation work.

The control wires are required to be mains-rated (600-v isolation and at least 1 mm cross-section). Since the system does not use polarity, installing the control-wire network is simplified. The wiring can be done in a star or bus topology (see Fig. 16.1). The star-wired network requires more cabling but offers reliable performance, while the bus network is initially less expensive but somewhat more difficult to maintain. If there is a problem with a cable in a bus network, the whole or at least part of the network is down.

The relatively-low communication speed of the DALI system (1200 bits per second) may, in large installations, lead to noticeable delays in the lighting reacting to input signals if many light changes are called for at the same moment. To stay within the permitted limits for voltage drop, the maximum control-line length is 300 metres. DALI can interconnect 64 different devices. It can however also be used as a subsystem with DALI gateways to address several groups of 64 devices.

Some controllers have the possibility to act both as a DALI controller and as a 1-10 volt controller: as, for example, the controller shown in Fig. 16.5. DALI can be combined, via converters or gateways, with other lighting-control systems such as 1-10 volt, DMX and LONwork systems. Integration with building-management systems that control non-lighting functions, such as cooling and heating, is possible as well.

### 16.3.4 DMX

DMX, or to use its full title DMX512, is a communication standard originally developed for use in theatres and discos for the control of different kinds of stage effects (including lighting) and such things as smoke machines.[35] It is now an ANSI standard (American National Standards Institute). Today it is used for the setting of lighting scenes in many lighting applications, both indoors and outdoors. It allows for the control of switching, dimming, colour changing, changing of aiming direction and change of beam shape (gobos).

DMX provides up to 512 control channels per data link. For the control of a single luminaire, more channels are usually needed: one for switching, one

35 DMX stands for Digital MultipleXed signal: multiple signals shared over a single network. DMX uses the RS485 communication method often used in data transmission.

for dimming, and so forth. For luminaire control, the digital messages are sent over the DMX network as eight-bit numbers corresponding to values between 0 and 255. This means, for example, that the dimming status can be controlled in 255 steps. For controlling the aiming direction of a narrow-beam spotlight this may not be sufficient, so more channels may be needed. Each luminaire or device being controlled has a DMX interface which, via the software (or via its hardware's dip switches), is given an address. In sequential order of the addresses, 512 messages (one for each channel-address) are continuously sent forty times per second (viz. with a repetition frequency of 40 Hz). Fig. 16.7 illustrates that the eight-bit message (with a value between 0 and 255) is sent in sequence of address. The combination of address and value of the digital signal instructs the luminaire being addressed to execute a certain action (dimming, colour changing, etc.). Different types of action can be allocated to specific address numbers via the software, thus to specific luminaires. Fig 16.8 shows an example of dimming commands sent to luminaires with different addresses. If for some reason the data is not interpreted the first time (because of noise, interference, etc.), it will be interpreted the next time the signal is received. By allocating different dimming channels to the red, green and blue LEDs of RGB LED units, instructions can be sent over the network to produce all the colours available from these units.

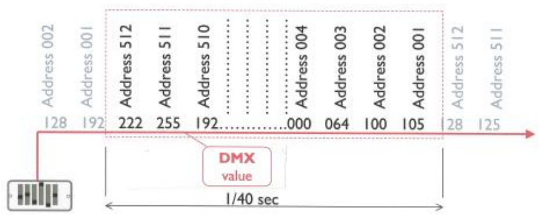



Fig. 16.7 DMX values (0-255) are repeatedly sent in sequence of address.

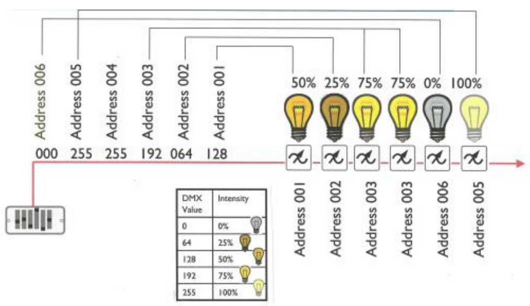



Fig. 16.8 The addressed DMX device knows which DMX value is being sent to it and dims to the corresponding light intensity.

The communication speed is high (250 000 bits per second), so that reactions to the messages are near-instantaneous. The DMX controller is connected to the devices in a serial bus topology that sequentially interconnects the devices via "in" "out" connectors on the device interfaces (Fig. 16.9)..[36] The total length of a DMX link can be up to about 500 metres and it allows for 32 devices on a single DMX link. So-called DMX splitters and boosters (signal amplifiers) can couple a large number of DMX links so that control systems can be made that include thousands of devices over distances of several kilometres. DMX-DALI converters allow DMX control systems to also control DALI-controlled luminaires.

Fig. 16.9 Serial bus topology of the DMX system.

RDM (Remote Device Management) is a protocol enhancement of DMX512 that allows for two-way communication over a standard DMX line. With this protocol, because feedback regarding the status of the controlled luminaires is received, the DMX control system can be extended into a lighting control and monitor system.

### 16.3.5 Power-line communication

Power-line communication (PLC) uses the electricity cable network for sending (modulated) data. It is popular with home automation (domotica), is sometimes used for internet access, and in recent years is seen more and more for the remote reading of electricity meters. In the far-distant past even complete radio programmes were transmitted over the power net. Power-line communication has been in use for some time for switching road-lighting installations in (two) lighting-level steps (for example, before and after midnight). It is now a communication method often used in intelligent road-lighting installations for both controlling and monitoring purposes. Transformers in the electricity network prevent propagating the signal which limits the data transmission to one building or area (as often wanted), unless special technological measures are taken.

36 The control cable is an RS485 shielded twisted pair consisting of two signal wires (in the case of a DMX control and monitor system, four signal wires) and a ground wire.

### 16.3.6 LonWorks

LonWorks is one of the lighting control and monitoring systems that often makes use of powerline communication.

Fig. 16.10 Logo of LonWorks.

LON (Local Operating Network) technology was originally developed by the American company Echelon for the aircraft industry in 1988. The purpose was to control all electronic components with totally different functions and from many different manufacturers through a reliable network. This has resulted in an independent open-network standard (ISO/IEC) that is, like DALI, based on decentralized intelligence. This means that once the network is configured, all or most of its data needed for control is not stored in a centralized control unit but in chips in the interfaces of the input and controlled devices.

Today, LonWorks is a common platform for building automation systems. LonWorks can make use of network media such as twisted-pair cables, power lines, fibre optics and wireless RF (wifi). A lighting control system can directly make use of LONwork if the input devices and controlled luminaires have an interface suitable for LONworks. There are input devices and controlled luminaires that are suitable for both LonWorks and DALI. As mentioned before, the DALI system can be combined with LonWorks, offering the possibility to connect building automation systems with the DALI lighting-control system.

LonWorks making use of powerline communication offers great possibilities for the control and monitoring of road-lighting installations over large areas. Since LEDs have more control possibilities than do traditional gas discharge lamps, such control systems are especially suitable for LED road-lighting installations. Fig. 16.11 shows a schematic of such a system.

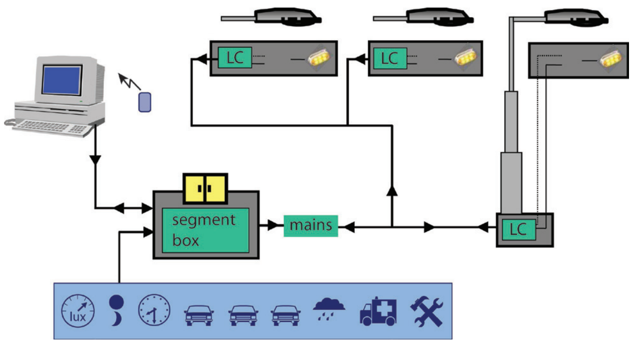



Fig. 16.11 Principle of a control and monitoring system for road lighting based on LonWorks and making use of powerline communication. The lighting is controlled on the basis of the actual lighting level measured, ambient lighting conditions (day/night), time, traffic density, weather conditions, accidents and road works. The lighting can be adapted by connecting a PC to the system or locally with a wifi connected smart phone. The powerline communication is two-directional so that information on the status of each individual luminaire is centrally available. (LC = lighting controller).

# 17 Index

# About the authors

## Prof. Wout van Bommel MSc

Wout van Bommel has worked 37 years with Philips Lighting Eindhoven in different lighting application functions. He was responsible for the company's international lighting application knowhow centre (LiDAC). Some concepts now used in international standards for lighting are based on his research work. For the period 2003 - 2007 he was President of the International Lighting Commission, CIE. He is a board member of the Dutch "Light & Health Research Foundation", SOLG. Wout van Bommel was in 2004 appointed Consulting Professor at the Fudan University of Shanghai. He has published more than 150 papers in national and international lighting journals. He is the author of the book "Road Lighting". All over the world he has presented papers, has taught at universities and schools and has given invited lectures at conferences.

After his retirement from Philips Lighting, he advices, as an independent Lighting Consultant, lighting designers, researchers, companies municipalities and governmental bodies.

## Abdo Rouhana MSc

Abdo Rouhana, a citizen of both Canada and Lebanon, graduated as an electrical engineer from the university of Montreal, Canada. After he got in 1983 from the same university his masters degree, he joined Philips Lighting in them Middle East, where he became lighting application specialist. He has been responsible for the design of many impressive lighting projects in the area. He combined this function with key positions in sales and marketing. Abdo Rouhana is now the head of Philips Lighting University, Middle East. He teaches lighting and lighting design at leading universities in the Middle East and for Philips Lighting in other parts of the world, including Philips headquarters in Eindhoven.

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