Correspondence Course
Lighting Application

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Lighting Design and Application Centre
Introduction

The tubular fluorescent (or ‘TL’ lamp, to use the Philips designation) is by far the most widespread of the discharge lamp types (Fig 1). It is employed almost universally in all types of commercial, social and civic interiors. In addition, tubular fluorescents are used in street and tunnel lighting, and also in increasing numbers in the home.

Comparatively new are the compact, high-performance fluorescent lamps, some of which can be used as direct replacements for incandescent lamps. These are marketed by Philips as PL and SV lamps in many varieties.

A logical consequence of the introduction of the compact-fluorescent lamp was the call for a very-small-diameter fluorescent lamp, the first of which have recently appeared on the market.

The latest development is the fluorescent induction lamp, a bulb-shaped, electrodeless lamp, which combines compactness with an unprecedentedly long operating life.

Unlike all other lamp types, fluorescent lamps are available in a wide choice of light colours to add even further to their versatility in application.

Not covered in this lesson are the special lamps that produce short-wave visible or ultraviolet radiation. These are used in a very wide range of applications: reprography, disinfection, tanning, inspection and analysis, various photochemical processes and effect lighting, to mention just a few. They operate on basically the same principle as other fluorescent lamps, but they are not always provided with a fluorescent coating. These types will be described in Lesson 12: UV Radiators and Applications.

Fig. 1 One of the huge ‘horizontal’ production units for Philips ‘TL’D fluorescent lamps.
1. Working principle

A ‘TL’ lamp is a low-pressure mercury lamp

The tubular fluorescent lamp works on the low-pressure mercury discharge principle (Fig. 2). The discharge tube has an electrode sealed into each end and is filled with a little mercury, the latter being present in both liquid and vapour forms.

The fluorescent coating converts UV into visible radiation

The inside of the tube is coated with a mixture of fluorescent powders. These convert the ultraviolet radiation of the mercury discharge into longer wavelengths within the visible range. A great many different fluorescent powders or ‘phosphors’ are available for this purpose, which by judicious mixing can produce light of almost any desired colour temperature and colour rendering characteristic.

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. With unheated electrodes, an auxiliary electrode is often provided in the form of a conductive strip along the inside of the tube wall.

Fluorescent lamps need a ballast and sometimes a starter as well

Unlike an incandescent lamp, a fluorescent lamp cannot be operated on its own in the circuit without some device to limit the current flow through it (see Lesson 7, Section 3.1). In addition to this device, which is termed a ‘ballast’, most types need a starter as well to switch the preheating current and to provide the high-voltage peak necessary for ignition. Moreover, in those countries with a 110/127 V mains voltage, larger fluorescent lamps also need some form of booster transformer, as otherwise the difference between the supply voltage and the voltage across the electrodes would be too small for the lamp to function properly.

Compact fluorescent lamps

In addition to the basic, straight tubular lamps, there is a large number of special types with a more compact form. These include circular, U and W-types, parallel-tube lamps (PL), and lamps in which the discharge tube is given a double bend (SL*). These compact lamps, which all work on the principle outlined above, often have an integral starter, and sometimes an integral ballast as well. In the latter case, they are provided with a standard screw or bayonet cap.

Small-diameter lamps

A recent development are small-diameter fluorescent lamps, with tube diameters as little as a few millimetres. They are either straight, or folded into a flat form. Small-diameter lamps require a higher operating voltage than standard lamps, but otherwise the performance characteristics are much the same. They are used in applications where space is very restricted and when special optical effects are required.

Fluorescent induction lamps

The QL induction lamp is also a fluorescent lamp, working on the low-pressure mercury principle. However, here the electric current flow through the gas mixture is not produced by a voltage difference across two electrodes sealed-in at the ends of the discharge tube, but by generating a high-frequency electromagnetic a.c. field in the discharge bulb by induction. The HF power signal is produced electronically and dissipated in the gas by means of an induction coil inside the bulb. QL-lamps need no separate control gear. The power generator is self-limiting and also generates the voltage peak necessary to initiate the discharge.
2. Construction

A tubular fluorescent lamp comprises the following main parts (Fig 3):
• tube
• tube coating(s)
• electrodes
• fill gas
• lamp caps
2.1 Tube

The tube of a normal fluorescent lamp is made of soda-lime glass that has been doped with iron oxide to contra the amount of short-wave transmission (Fig. 4). The tube is drawn from a high-capacity glass oven in a continuous process, and then cut to length (Fig. 5).

The tube length and diameter have been standardised (Fig. 6). Five standard tube diameters have been adopted: 5/8 inch (16 mm), 1 inch (26 mm), 1 1/4 inch (32 mm), 1 1/2 inch (38 mm) and 2 1/8 inch (54 mm). In the USA, these are designated T5, T8, T10, T12 and T17 respectively, the number standing for the diameter expressed in eighths of an inch (T10 and T17 lamps are hardly ever found outside America).

The diameter of the tube is determined by the discharge current and the permissible radiant load on the fluorescent layer (i.e. the wall loading). Since 1978, there has been a general tendency to abandon the larger tube diameters - at least for switch-start lamps - and to standardise upon 26 mm. In the main, this has been made possible by the introduction of narrow-band fluorescent powders that are better able to withstand high wall loadings.

Tube length is dictated in the first place by the luminous flux to be produced by the lamp and by the voltage across the discharge tube (i.e. the lamp voltage). But the deciding factor is the need on the part of the luminaire industry to adopt tube lengths compatible with standard building modules. The most commonly used tube lengths - or rather lamp lengths - are 2 ft (600 mm), 4 ft (1200 mm) and 5 ft (1500 mm), but the complete range includes lengths ranging from 150 mm (1/2 ft) to 2400 mm (8 ft), or even longer.
2.2 Tube coatings

2.2.1 Fluorescent coating

The fluorescent coating determines the light characteristics

The most important factor in determining the light characteristics of a fluorescent lamp is the type and composition of the fluorescent powder used. This fixes the colour temperature, the characteristics colour rendering index ($R_a$) and, to a large extent, the luminous efficacy of the lamp.

Fluorescent powders (also called 'phosphors') are very much a product of modern chemical technology. Although a few naturally occurring minerals exhibit fluorescence, most chemical compounds will only do so after having been purified to the highest degree, a small amount of another compound (the 'activator') having then been added. It is the activator that principally determines the spectral characteristics of the fluorescent light. Some fluorescent powders, like Apatite, have two activators.

A large number of fluorescent compounds have been discovered over the years, with emission curves ranging from the infrared to long-wave ultraviolet. The most important for fluorescent lamps are listed in the accompanying table.

Wide and narrow-band

Some fluorescent powders, like Apatite and other halophosphates, show an emission band covering almost the whole visible spectrum, and therefore produce 'white' light when used alone (Fig. 7). Where extremely good colour rendering is required, however, a combination of fluorescent powders with different colour characteristics is used.

The fluorescent lamps in the Philips 80-series employ a mixture of fluorescent powders having very narrow emission hands in blue, green and red, viz. BAM, CAT or CBT, and YOX (Fig. 8). By changing the proportions of the three powders, any colour point in the CIE colour triangle situated between the colour points of the Individual compounds can be obtained (see Fig. 9 and also Lesson 3, Section 7.2.2).

As the three emission bands are equally distributed over the visible spectrum, good average colour rendering is achieved in combination with a high luminous efficacy. However, narrow-band phosphors are comparatively expensive, and to keep the amounts needed as low as possible the tube wall is first coated with a thin layer at halophosphate before the narrow-band phosphors are applied. The halophosphate coating accounts for only ten per cent of the visible radiation.

For the lamps in the 90-series, where excellent colour rendering is of first importance, a combination of four or five wide-band phosphors is used, also applied in two layers. Thus, the entire visible spectrum becomes evenly covered.

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*Fig. 7 Typical spectral emission curve of double-Activated calcium halophosphate (Apatite).*

*Fig. 8 Spectral emission curves of the phosphors used in Philips fluorescent lamps of the 80-series.*
Factors Influencing the efficiency of the fluorescent coating

Lamp efficiency much depends also on certain physical characteristics of the tube coating such as the thickness of the layer and the fineness of the powder. Ideally, the powder should be coarse enough to obtain the highest efficiency of conversion from ultraviolet into visible radiation, and the layer as thin as possible to prevent it from absorbing too much visible radiation. But it must not be too thin, or it will be transparent to the ultraviolet radiation from the discharge, the more so if a powder of a coarse crystalline structure is used. So a compromise has to be found, resulting in an average thickness of three layers of crystals (Fig. 10).

In practice, this is not enough to filter out all the visible and nearby ultraviolet radiation *) from the discharge: some of it will ‘break’ through the fluorescent layer. For most applications this is of little consequence, but where it is considered unacceptable for the lamp to emit UV - as for example in lamps intended for use in museums - the blue and violet lines can be suppressed by applying an extra layer of a non-fluorescent material (mostly nickel titanate).

*) Only UV radiation in the 365-nm range has a chance of actually leaving the lamp. The 254 nm line will mostly be converted into visible radiation, what is left being completely absorbed by the glass of the tube.
This, however, is at the cost of luminous efficacy, and for the lamps manufactured by Philips this practice has been discontinued, especially since the short-wave transmission properties of the glass tubing can be exactly controlled.

**Characteristics of important fluorescent powders**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Activator</th>
<th>Peak wavelength (nm)</th>
<th>Commercial name</th>
</tr>
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<tbody>
<tr>
<td>Strontium aluminate</td>
<td>cerium</td>
<td>307</td>
<td>S-IC</td>
</tr>
<tr>
<td>Gadolinium lanthanum bismuth borate</td>
<td>-</td>
<td>312</td>
<td>SLBE</td>
</tr>
<tr>
<td>Barium disilicate</td>
<td>lead</td>
<td>349</td>
<td>BSP</td>
</tr>
<tr>
<td>Strontium barium magnesium silicate</td>
<td>lead</td>
<td>365</td>
<td>SMS</td>
</tr>
<tr>
<td>Strontium tetraborate</td>
<td>europium</td>
<td>368</td>
<td>SOE</td>
</tr>
<tr>
<td>Calcium tungstate</td>
<td>-</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>Strontium pyrophosphate</td>
<td>europium</td>
<td>418</td>
<td>SPE</td>
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<td>europium</td>
<td>447</td>
<td>BAM</td>
</tr>
<tr>
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<td>antimony</td>
<td>482</td>
<td>Calcium Blue</td>
</tr>
<tr>
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<td>europium</td>
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<td>SAE</td>
</tr>
<tr>
<td>Strontium halophosphate</td>
<td>antimony</td>
<td>490</td>
<td>Strontium Blue</td>
</tr>
<tr>
<td>Strontium halophosphate</td>
<td>antimony</td>
<td>502</td>
<td>Strontium Blue</td>
</tr>
<tr>
<td>Barium magnesium aluminate</td>
<td>europium &amp; manganese</td>
<td>514</td>
<td>BAM Green</td>
</tr>
<tr>
<td>Zinc silicate</td>
<td>manganese</td>
<td>525</td>
<td>Willemite</td>
</tr>
<tr>
<td>Cerium terbium magnesium aluminonate</td>
<td>-</td>
<td>541</td>
<td>CAT</td>
</tr>
<tr>
<td>Cerium gadolinium magnesium borate</td>
<td>terbium</td>
<td>542</td>
<td>CBT</td>
</tr>
<tr>
<td>Yttrium aluminonate</td>
<td>cerium</td>
<td>563</td>
<td>YAG Ce</td>
</tr>
<tr>
<td>Calcium halophosphate</td>
<td>antimony &amp; manganese</td>
<td>579-585</td>
<td>Apatite</td>
</tr>
<tr>
<td>Yttrium oxide</td>
<td>europium</td>
<td>610</td>
<td>YOX</td>
</tr>
<tr>
<td>Yttrium vanadate phosphate borate</td>
<td>europium</td>
<td>618</td>
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<td>Cerium gadolinium terbium magnesium borate</td>
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</tr>
<tr>
<td>Lithium pentaaluminonate</td>
<td>iron</td>
<td>743</td>
<td></td>
</tr>
</tbody>
</table>

**2.2.2 Other coatings**

In addition to being coated with fluorescent powder, tubes of fluorescent lamps sometimes receive a special, extra coating.
Silicone coating
This water-repellent coating is applied to the outside of those fluorescent lamps used in starterless circuits to prevent starting problems under conditions of high humidity.

Conductive coating
Some types of fluorescent lamps for use in rapid-start circuits receive a conductive coating, consisting of tin or indium dioxide, between the tube wall and the fluorescent layer to ensure reliable starting over a wide range of temperatures. This is an alternative to the external conductive strip (see Section 4.2.2).

Reflector lamps
These lamps are given an extra coating over part of the circumference, consisting of an opaque white powder (aluminium oxide) between the tube wall and the fluorescent coating. The light leaves the lamp through the strip or 'window' remaining, which is only coated with the normal fluorescent powder (Fig. 11 left).

Aperture lamps
These are similar to reflector lamps as regards their construction, but here the window is left completely uncoated (Fig. 11 right and Fig. 12).

2.3 Electrodes

The electrodes provide the free electrons for discharge
The lamp electrodes, which are coated with a suitable emitter material, serve to conduct electrical power into the lamp and provide the electrons necessary to maintain the discharge. Construction details vary, but an electrode consists basically of a tungsten filament coated with a crystalline material that readily releases electrons when heated to a temperature of about 800°C. A mixture of the oxides of barium, strontium and calcium has been found the most suitable emitter material for use in fluorescent lamps.

Most electrodes are preheated by an electric current prior to lamp ignition, and for this reason are made the same shape as the tungsten filament used in an incandescent lamp. However, they are often triple-coiled (Fig. 13), or wound round (intertwined) with a thin wire (Fig. 14), in order to hold as much emitter material as possible.

Preheated, continuously heated and cold electrodes
The normal preheating voltage is 3 volts for most lamp types, although some employ 8 to 10 volt electrodes, especially in Great Britain. Once the lamp is burning, the preheating current is switched off and the high temperature necessary for a free emission of electrons is maintained by the bombardment of the electrodes by fast ions emanating from the discharge. This is the most frequently employed construction. There are, however, fluorescent tubes that have continuously heated electrodes – 'rapid-start' lamps - and those that have electrodes that
are not preheated – ‘cold-start’ or ‘instant-start’ lamps. The electrodes of cold-start lamps are of a heavier construction to carry more emitter material. Both types are used in circuits without a separate starter, and often employ some form of auxiliary electrode or conductive strip to facilitate ignition.

During its life, the electrode loses emitter material due to evaporation and scattering as a result of the ion bombardment from the discharge. This is the chief cause of eventual lamp failure. The electrode supports employed in fluorescent lamps having heated electrodes are constructionally similar to the filament supports of GLS incandescent lamps. They consist of a lead-glass stem with exhaust rod, lead-in wires, and support wires for the filament.

In most fluorescent lamps, the electrode support carries a flat metal ring. This surrounds the filament and so prevents scattering emitter material from settling on the nearby tube wall, which would cause blackening in the form of the so-called ‘end bands’.

The electrode support also carries the mercury capsule

At one end of the fluorescent tube only, a small metal or glass capsule is attached to the ring or stem (Fig. 15). This capsule contains the liquid mercury (some 5 to 15 milligrammes) needed in the discharge tube end after the tube has been evacuated and sealed.
2.4 Fill gas

The gas fill in a fluorescent lamp consists of a mixture of saturated mercury vapour and an inert buffer gas in a ratio of approximately 1:3000 when the lamp is operating.

2.4.1 Inert gas

Functions of the inert gas

The inert gas has three primary functions:

1. It controls the tree-path length, and thus the speed, of the free electronics in the discharge, as otherwise these would produce ionisation rather than excitation of the mercury vapour atoms.
2. It prolongs the life of the electrodes by reducing sputtering and evaporation of the emitter material as a result of a too intense ion bombardment.
3. It facilitates ignition by providing easier breakdown at a lower ignition voltage, especially at low temperatures.

The most commonly employed buffer gas is argon, which is mixed with up to 25 per cent neon to achieve the most effective free-electron velocity. Fluorescent lamps of 26 mm diameter, that are intended to operate in the same type of circuit as older 38 mm lamps (e.g. Philips 'TL'D lamps for conventional, non-electronic, ballasts), have heavier krypton added to the fill gas in order to obtain the same lamp voltage for the smaller diameter lamp*), although the starting voltage will be higher.

2.4.2 Mercury

Under normal operating conditions, mercury is present in the discharge tube in both liquid and vapour forms. The mercury vapour pressure is strongly influenced by temperature. The highest light output is achieved for a gas temperature of 40°C at the coolest spot in the discharge tube. The equivalent mercury vapour pressure is then approximately 0.8 Pa.

*) For a given tube length, lamp voltage increases with decrease in tube diameter and decreases as the atomic weight of the gas increases.

Fig. 16 Low-pressure mercury spectrum, showing that most of the radiant energy is emitted in the in the 185 nm and 254 nm bands.
compared with a pressure of the buffer gas of about 2500 Pa (0.025 atmosphere). Under these conditions, about 90 per cent of the radiant energy is emitted in the 185 nm and 254 nm UV bands (Fig. 16). Higher or lower temperatures will result in a higher or lower mercury vapour pressure and a shift in the emission characteristics, in both cases resulting in a decrease in light output. The reasons for this will be dealt with further in Section 3.3.1.

2.4.3 Mercury amalgam

The temperature of the coldest spot in the discharge tube, which will normally be the inside of the tube wall in the middle of the lamp, determines the mercury vapour pressure and consequently the light output of the fluorescent lamp. Ideally, this temperature must be 40°C, corresponding to an ambient temperature of 25°C in still air.

In fully enclosed luminaires (thus without ventilation), a temperature of greater than 25°C is easily reached. To eliminate the disadvantage of a drastically reduced light output, the lighting industry has developed fluorescent lamp types that maintain a constant luminous flux at higher ambient temperatures. This is achieved by adding the mercury to the fill gas in the form of an amalgam, rather than as a pure metal. An amalgam is a chemical compound consisting of mercury and one or more other metals. The mercury vapour pressure above an amalgam is lower than that above pure liquid mercury under comparable conditions, and also increases less with temperature until the amalgam is completely molten. Thus a nearly constant light output is obtained over a temperature range from 15°C to 70°C (Fig. 17).

A bismuth-indium amalgam has been found to be the most suitable for fluorescent lamps. It is, for example, used in the Philips SL*, PL-T, PL*E/T and QL lamps. But its use in normal fluorescent lamps has been discontinued, since krypton-filled 'TL'D lamps operate quite satisfactorily at high temperatures.

Amalgam-riffed lamps are used at high ambient temperatures

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Pg. 17 *Lumirraus thuxas* a of tempera Me P~ amalgam lamp, compared Mt~i a flOr3lia~ 33 mm lamp.
2.5 Lamp caps

The variety of lamp caps employed with tubular fluorescent lamps is not as wide as that found with incandescent lamps.

**One, two and four-pin caps**

A tubular fluorescent lamp with heated filaments needs two caps, one at each end, and each having two contacts. Cold-start lamps employ single-contact caps. Circular lamps have a single, four-contact cap.

The lamp contacts are mostly of the pin-and-socket type. Highly-loaded lamps or lamps employing auxiliary electrodes have recessed contacts. The designation of caps for fluorescent lamps follows the IEC code of practice described in Lesson 8, Section 2.5.2. The following types are commonly in use (Fig. 18):

- **Two contacts**
  - G5 for 16mm (miniature) lamps
  - G13 for 26 mm, 32 mm and 38 mm lamps
  - G20 for 54 mm lamps
  - R17d (recessed contacts) for 38 and 54 mm lamps

- **Four contacts**
  - G10q for circular lamps

- **One contact**
  - Fa6 for lamps used in areas where there is an explosion risk
  - FaS for cold-start lamps of the ‘Slimline’ type
  - R18s (recessed contact) for other cold-start lamps

Single-ended (compact) fluorescent lamps often employ specially designed two or four-pin lamp caps. Those with integrated control gear have standard E26 or E27 screw or B22 bayonet caps to fit in GLS incandescent lamp holders. Very narrow-diameter lamps also use special types of contacts.

*Fig. 18 Caps for fluorescent lamps.*
3. Performance characteristics

3.1 Energy balance

Before going on to examine the various performance characteristics of the fluorescent lamp, it would be useful to take a look at the energy balance of a typical lamp. Fig. 19 shows the energy balance of a TL'D fluorescent lamp of 36 W, colour 82, operated in still air with an ambient temperature of 25°C. It appears that approximately 30 per cent of the input power is emitted in the form of visible radiation and about a half percent in the form of long-wave UV radiation. The rest is ‘lost’ in the form of heat.

Heat losses chiefly result from:
- the heating of the electrodes as a result of the constant bombardment with fast ions from the discharge;
- thermal processes in the discharge itself resulting from elastic collisions that do not lead to excitation or ionisation;
- heat generated in the fluorescent layer as a result of absorption of UV and visible radiation from the discharge, and the quantum losses inherent in the process of fluorescence (see Section 3.3.2).

3.2 Influence of ambient temperature on light output

In the discharge itself, three processes involving the transfer of energy take place (see also Lesson 3, Section 1.3.1):
1. Collisions between free electrons and gas atoms in which the atomic structure of the latter is not changed. The energy transfer only results in a change of direction or speed, or both.
2. Collisions between free electrons and gas atoms with sufficient energy to bring the atom into an excited state. An electron of the atom is sent into an orbit of higher energy, only to return to its stable orbit a fraction of a second later, thereby emitting a quantum of electromagnetic radiation.
3. Collisions between free electrons and gas atoms in which the energy at impact is so great as to cause ionisation. One or more electrons are completely released from the atom, thereby forming more free electrons and positively-charged ions.

Only collisions of the second type produce electromagnetic radiation. Conditions are therefore created that encourage the occurrence of this type of collision.

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About two-thirds of the input power is converted into heat

Three types of collisions

![Fig. 19 Energy balance of a 36 W fluorescent lamp, colour 82.](image)
Influence of the mercury vapour pressure

At normal operating temperatures, the carrier gas atoms (argon, neon or krypton) outnumber the mercury atoms by a factor of 3000 to 1, but nevertheless the chance of exciting a mercury atom is much greater, because only about half the energy is needed to bring an electron into an excited orbit.

Mercury is present in both its liquid and gaseous forms. The liquid mercury will be found at the coolest place, that is to say on the tube wall. The vapour pressure of the gaseous mercury is determined by the temperature of the coolest spot. With an increase in temperature, liquid mercury will evaporate resulting in a higher vapour pressure. Conversely, with a decrease in temperature, mercury vapour will condense out into tiny drops on the cool spot, resulting in a drastically reduced vapour pressure.

At low temperatures, there will thus be insufficient gaseous mercury atoms in the discharge in relation to the availability of free electrons. The light output of the lamp will therefore rapidly decrease at ambient temperatures below 15°C. At high temperatures, on the other hand, there will be so many mercury atoms in the gaseous state that they will absorb each other’s radiation, converting it into non-radiant heat. Thus, with increasing temperature the light output will also decrease, be it at a slower rate (Fig. 20).

Ways to maintain the correct mercury pressure

The output of radiation reaches a maximum at a mercury vapour pressure of approximately 0.8 Pa. The corresponding cool-spot temperature is 40°C. For non-insulated tubular fluorescent lamps, this value is reached at an ambient temperature of 25°C in still air which happily coincides with the ceiling temperature in most interiors.

In the case of heavily loaded fluorescent lamps or those used in fully enclosed, unventilated luminaires, it is generally impossible to maintain the cool-spot temperature as low as 40°C. To avoid a consequent decrease in light output, special measures are therefore adopted.

There are two solutions open:

1. To modify the lamp construction in such a way that cooler-than-normal spots are created at places remote from the discharge. This can be the space behind the electrodes - obtained by mounting these on extra-long stems - or groves, dimples, etc., provided in the tube wall (Fig. 21). Some types for special applications are even provided with cooling fins.

2. To fill the lamp with a mercury amalgam instead of pure mercury. The amalgam is solid under normal operating conditions and therefore the mercury vapour pressure above the solid amalgam will, for a given temperature, be lower than above liquid mercury. This pressure will also increase at a much slower rate until the melting point of the amalgam is reached (approximately 100°C).
3.3 Luminous efficacy

Lamp efficacy and system efficacy

When defining the luminous efficacy of a fluorescent lamp (and of any other discharge for that matter), a clear distinction must be made between lamp efficacy and system efficacy. The latter, as the name suggests, also takes into consideration the energy losses in the circuitry in which the lamp is operating. Although it would be more relevant to always express luminous efficacy in terms of system efficacy, the problem is that this is influenced by the type of circuitry and the components used, factors that are generally beyond the control of the lamp manufacturer.

There are, however, lamp constructions (such as the SL* and PL* Electronic lamps) where the lamp and ballast form a single, integral unit. In such cases it is the system efficacy that is specified, rather than the lamp efficacy.

Many factors influence luminous efficacy

The luminous efficacy of a fluorescent lamp is influenced by many factors: lamp power, lamp dimensions, electrode construction, type and pressure of the fill gas, chemical and physical properties of the fluorescent layer, characteristics of the supply voltage, and ambient temperature. Some of these factors merit closer examination.

3.3.1 Influence at temperature

Just as with the light output, the luminous efficacy of the tubular fluorescent lamp decreases if the ambient temperature is above or below the optimum value. However, since the power dissipated by the lamp also decreases rapidly with increase in temperature (especially in a capacitive circuit), the luminous efficacy will in fact fall off less rapidly than the luminous flux (Fig. 22).

3.3.2 Influence of the fluorescent layer

The most important

In the absence of a fluorescent coating, the luminous efficacy of the low-pressure factor mercury discharge would be in the order of 5 lm/W. The most efficient powders available for 'white' light permit an efficacy of about 100 lm/W to be attained. Clearly, the nature of the fluorescent layer is the most important single contributing factor in determining the luminous efficacy of the fluorescent lamp.

Quantum efficiency of phosphors

The process of fluorescence is accompanied by a loss of radiant energy. This comes about in two ways. Firstly, inherent in the process, is the fact that each quantum of short-wave incident radiation releases a single quantum of a longer wavelength, and this according to
Planck’s Law*) - is of a lower energy level (see Lesson 3, Section 4). For the predominant UV wavelength in the low-pressure mercury discharge of 254 nm, this ‘quantum ratio’ is approximately 70 per cent at the short-wave (violet) end of the visible spectrum but drops to 30 per cent at the red end. In combination with the low eye sensitivity for deep red, this explains how a considerable increase of luminous efficacy can be achieved by omitting the longest spectral wavelengths, which is in fact normal practice if less-than-excellent colour rendering is required.

Absorption losses

Further losses occur as a result of the transmission or absorption of UV radiation that is converted into visible light. And then there is the subsequent absorption of visible light already converted. In both cases, the ultimate result is heat. The thickness and crystalline structure of the fluorescent layer determine the degree of these losses, which seldom amount to more than a few per cent.

Finally, the luminous efficacy is influenced by the spectral distribution of the light. The higher the proportion of radiation emitted in those wavebands for which the eye is most sensitive, the higher the luminous efficacy will be, but generally at the cost of colour rendering.

In practice, luminous efficacy of the tubular fluorescent lamp ranges from 40 lm/W to 100 lm/W for the higher wattage types.

*) According to Planck’s Law, the energy of a quantum equals $h \cdot v$ or $\frac{h \cdot c}{\lambda}$. Thus, for example, the quantum ratio of visual radiation of 589 nm to UV radiation of 254 nm will be $\frac{254 \times 100}{589} = 43\%$.
3.3.3 Influence of supply frequency

An a.c. discharge at mains frequency behaves as a d.c. discharge

The great majority of fluorescent lamps are run on the 50 Hz or 60 Hz a.c. mains. At this low frequency, the discharge characteristics are the same as for d.c. supply, with the function of the electrodes changing from anode to cathode and back every half cycle. The same happens to the cathode and anode fall, the steep voltage drop in the discharge near the surface of the electrodes (see Lesson 7, Section 1.3.1). As has been explained there, the cathode fall is caused by a positive space charge at a short distance from the negative electrode, which is the result of a local excess of positive ions. The anode fall, on the other hand, is caused by a shortage of positive ions close to the anode, resulting in a potential drop. It is influenced by many factors, for example the surface area of the anode, a larger surface generally resulting in a lower anode fall*).

In a typical fluorescent tube, the cathode fall is of the order of 9 volts, and the anode fall about 5 volts (Fig. 23). It causes an appreciable proportion of the power in the discharge to be dissipated near the electrodes, where it does not produce any radiation: but merely serves to heat them.

Above 1000 Hz the anode fall disappears, resulting in a higher luminous efficacy

At frequencies above approximately 1000 Hz the situation changes, the ionisation of the gas no longer being able to follow the rapid changes of the wave cycle. The positive space charge near the cathode persists during the half of the cycle when the electrode serves as the anode, and thus absorbs the electrons instead of the anode surface doing this. The consequence is that the anode fall becomes practically zero.

In practice, operation on a high-frequency supply will cause a reduction of the combined electrode fall from approximately 14 volts to 9 volts, resulting in an increase of the luminous efficacy of about 10 per cent. This is the main reason why the lamp efficacy is generally improved by employing HF Electronic ballasts (which operate at 28 kHz), although minor alterations in the lamp design and a more favourable waveform of the supply voltage play a role as well.

3.4 Colour appearance and colour rendering

3.4.1 Colour appearance

Broad division of fluorescent lamp colours

The (correlated) colour temperature of ‘white’ fluorescent lamps varies between approximately 2700 K and 7500 K. The International Electrotechnical Commission (IEC) has suggested the

*) Increasing the surface to reduce the anode fall is not feasible with an a.c. supply, as this would impair its performance as a cathode.

Fig. 23 Electrode fall of a ‘TL’ D 18 W fluorescent lamp with 50 Hz supply and with high-frequency supply.
following broad division of colour appearance, according to their colour temperature, for application purposes:

<table>
<thead>
<tr>
<th>Colour appearances</th>
<th>Colour temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>warm-white</td>
<td>3000 K</td>
</tr>
<tr>
<td>white</td>
<td>3500 K</td>
</tr>
<tr>
<td>cool-white</td>
<td>4200 K</td>
</tr>
<tr>
<td>daylight</td>
<td>6500 K</td>
</tr>
</tbody>
</table>

### 3.4.2 Colour rendering

Another colour division can be made on the basis of the colour rendering index (or $R_a$) of a lamp. Lamps with an $R_a$ of less than 80 give only moderate colour rendering. Such lamps are suitable for outdoor and orientation lighting, and for those industrial activities where colour discrimination is not critical. Lamps with a colour rendering index between 80 and 90 generally find application in commercial and social premises and also in the home. Finally, lamps with the best colour rendering, viz, with an $R_a$ of over 90, are employed in those situations where colour rendering requirements are particularly critical, as in museums, hospitals, certain types of shops, graphic and design studios and other places where the work involves the accurate matching or judging of colours.

The following table gives the colour temperatures and colour rendering indexes of the various Philips standard ‘TL’ colours (including some that are no longer in production but that are still in use). The average colour rendering index ($R_a$) is based upon fourteen test colours, and the luminous efficacy is quoted for the 36/40 watt version. The spectral power distribution of the present ‘TL’ colours is given in Fig. 24.

### Limitations of the $R_a$ system

Finally, a word of caution with regard to the significance of the colour rendering index. In the first place, it should be remembered (see Lesson 7, Section 7.4) that the $R_a$ of a ramp is in fact an average value based on the examination of eight or fourteen test colours. Secondly, a low $R$-value for a certain colour can mean that the hue of the colour will shift, that the colour will be poorly (weakly) rendered or that the colour will be exaggerated, perhaps even with a flattering effect.

Colour exaggeration is exemplified by the ‘TL’ colour 79, which shows a boost in the 600 - 700 nm region of the visible spectrum. Colour 79 lamps therefore render the deep red colours particularly well, which helps to emphasize the fresh appearance of red meat and similar products. Nevertheless, the average colour rendering index $R_a$ of these lamps is ‘only’ 72.

Because it is an average value, a seemingly acceptable $R_a$ can be obtained despite the fact that the colour rendering of one of the test colours is particularly bad. This is by no means a theoretical concept. Many fluorescent lamps have problems with test colour $R_a$ (deep red), the colour rendering index for which may drop as low as -18 (for the ‘TL’ colour 82 lamp) or even -110 (for the colour 29 lamp). But there are also lamps that render this colour fair to good (e.g. 83 for ‘TL’ colour 95), and it will be clear that where reds or purples have to be faithfully rendered, the choice of the right light colour is very important, much more so than if greens or yellows are the predominant colours, as good colour rendering of these gives no problem with most fluorescent lamps. It will also be clear that some degree of exaggeration in the rendering of certain colours is not always necessarily a drawback, as for example in a food or flower shop.

Needless to say, lamp designers are fully aware of the limitations of the system. In practice, therefore, a lamp having an average colour rendering index of better than 90 can generally be relied upon to give a good rendering of all the individual test colours.
Fig. 24 Spectral energy distributions of all principal Philips ‘TL’ colour.

**Standard colours**

- **Colour 29**
  - $T = 2900$ K
  - $R_a = 51$

- **Colour 35**
  - $T = 3400$ K
  - $R_a = 57$

- **Colour 33**
  - $T = 4100$ K
  - $R_a = 63$

**Three-band colours**

- **Colour 82**
  - $T = 2900$ K
  - $R_a = 81$

- **Colour 83**
  - $T = 2900$ K
  - $R_a = 82$

- **Colour 84**
  - $T = 3800$ K
  - $R_a = 90$

**Multi-phosphor colours**

- **Colour 92**
  - $T = 2700$ K
  - $R_a = 94$

- **Colour 93**
  - $T = 3000$ K
  - $R_a = 95$

- **Colour 94**
  - $T = 3800$ K
  - $R_a = 96$

**Special colours**

- **Colour 79**
  - $T = 3800$ K
  - $R_a = 72$

- **Colour 85**
  - $T = 5000$ K
  - $R_a = 80$

- **Colour 95**
  - $T = 5000$ K
  - $R_a = 98$

- **Colour 89**
  - $T = 10000$ K
  - $R_a = 70$

- **Colour 54**
  - $T = 6200$ K
  - $R_a = 72$

- **Colour 96**
  - $T = 6500$ K
  - $R_a = 98$
### Survey of Philips ‘TL’ colours

<table>
<thead>
<tr>
<th>Colour group</th>
<th>Philips colour code *)</th>
<th>Colour temperature (K)</th>
<th>Colour rendering index (R&lt;sub&gt;a&lt;/sub&gt;)</th>
<th>Luminous efficacy (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm-white</td>
<td>R&lt;sub&gt;a&lt;/sub&gt; &lt; 80</td>
<td>29</td>
<td>2900</td>
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<td>82</td>
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<tr>
<td></td>
<td>R&lt;sub&gt;a&lt;/sub&gt; &gt; 90</td>
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<td>94</td>
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<td>3000</td>
<td>95</td>
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<td>35</td>
<td>3400</td>
<td>57</td>
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<tr>
<td></td>
<td></td>
<td>79 **)</td>
<td>3800</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>80 &lt; R&lt;sub&gt;a&lt;/sub&gt; &lt; 90</td>
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<td>3700</td>
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<td>91</td>
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<tr>
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<td></td>
<td>94</td>
<td>3800</td>
<td>96</td>
</tr>
<tr>
<td>Cool-white</td>
<td>R&lt;sub&gt;a&lt;/sub&gt; &lt; 80</td>
<td>33</td>
<td>4100</td>
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<tr>
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<td>95</td>
<td>5300</td>
<td>98</td>
</tr>
<tr>
<td>Daylight</td>
<td>R&lt;sub&gt;a&lt;/sub&gt; &lt; 80</td>
<td>54</td>
<td>6200</td>
<td>72</td>
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<td></td>
<td>86</td>
<td>6300</td>
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<tr>
<td></td>
<td>89 **)</td>
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<tr>
<td></td>
<td></td>
<td>57</td>
<td>7300</td>
<td>94</td>
</tr>
</tbody>
</table>

*) The USA employs a different system of colour codes.
**) Lamps for special applications.

### 3.5 Lamp life and depreciation

#### 3.5.1 Lamp life

The end of life for a fluorescent lamp is generally reached when so much of the emitter material on the electrodes has come off (as a result of the constant bombardment with ions from the discharge, see Fig. 25) that the lamp’s operating voltage has become too high in relation to the supply voltage, and the lamp no longer starts. This process is accelerated by several factors, such as insufficient preheating of the electrodes, excessive switching, and sharp peaks in the lamp current (Fig. 26).

**Cold starts and sharp current peaks drastically shorten lamp life**

In a preheat lamp circuit, it is essential that the electrodes be brought up to the proper temperature (about 800°C) before any attempt is made to start the lamp. Failure to do so will drastically shorten the life of the lamp. If proper preheating is taken care of, the effect of the frequency of the switching on lamp life is much less pronounced. Fig. 27 shows the influence of the switching frequency on lamp life under rated conditions.

With regards to the sharp peaks in lamp current, these must not be such that the ‘peak factor’ specified by the lamp manufacturer is exceeded. This is defined as the ratio of the peak value of the lamp current to the r.m.s. value. The maximum permissible peak factor is 1.7.
Unfortunately, even a good-quality choke ballast will give a value close to this maximum, while for high-frequency electronic ballasts the peak factor is close to unity. This is one of the reasons why lamps operated on electronic ballasts have a longer average life than those operated on traditional ballasts. Fig. 28 gives the life expectancy curves of fluorescent lamps operated on traditional choke and HF electronic ballasts, respectively.

### 3.5.2 Depreciation

Deterioration of the phosphors is the main cause of depreciation During the life of a fluorescent lamp the luminous flux decreases. After 8000 hours it will be between 70 and 90 per cent of the initial value. The main cause of depreciation is that the fluorescent powders slowly become less effective, probably as a result of chemical attack by mercury ions. The depreciation rate depends upon the wall loading - defined as the ratio of lamp current to wall area - and the type of fluorescent powder(s) employed, three-band phosphors showing considerably less depreciation than halophosphates (Fig. 29). When mixtures of different fluorescent powders are used, it may happen that older lamps will show a slight discolouration compared with new ones.

A secondary cause of depreciation is the blackening of the tube wall - especially at its ends - by dispersed emitter material. As has been explained in the previous section, employing high-frequency electronic ballasts will result in less sputtering of the emitter material, which, in turn, will give a lower depreciation rate.
4. Lamp circuits

4.1 Current limitation

Four ways of limiting the current

As has already been pointed out (see Lesson 7, Section 3.1), the discharge lamp has a negative resistance characteristic and so must be operated in conjunction with a current limiting device, or ballast, to prevent current runaway. The ballast, which has a positive resistance characteristic, can be:

- a resistor
- a capacitor
- a choke or inductor
- an electronic circuit

Each has its specific advantages and disadvantages, as will be discussed in the following section, but every type has found practical application in some form.

4.1.1 Types of ballasts

Resistor ballasts

This is a very uneconomic form of current limitation, because electrical energy is dissipated in the form of heat. On the other hand, until the advent of electronic circuitry, a series resistor was the only way to stabilise fluorescent lamps operated on d.c. (Fig. 30).

An incandescent lamp serves well as a d.c. ballast

For stable operation on a resistor ballast, it is necessary that the supply voltage be at least twice the lamp voltage under operating conditions. This means that fifty per cent of the power will be dissipated by the ballast. A considerable improvement in efficiency, however, can be achieved by using a resistor with a very pronounced positive temperature characteristic (a common or specially constructed incandescent lamp serves well for this purpose, see Fig. 31). A temperature-dependent resistor compensates for variations in the lamp current resulting from variations in the mains voltage, which means that the no-load voltage need be no more than 25 to 30 per cent higher than the lamp voltage. This is also the proportion of the power dissipated by the ballast compared to the total circuit power.

Capacitor ballasts

A capacitor used as a ballast exhibits only very little losses, but cannot be used by itself as this would give rise to very high peaks in the lamp-current waveform at each half cycle. Only at very high frequencies can a capacitor serve satisfactorily as a ballast.

Fig. 30 Schematic diagram of a fluorescent lamp operated on a resistor ballast in a d.c. circuit.

Fig. 31 D.C. resistor ballast or stabilisation lamp.
**Inductive ballasts**

A choke is the most common type of ballast. An inductor or choke exhibits somewhat higher losses than a capacitor, but produces far less distortion in lamp current at 50 Hz. This makes it the ideal ballast for normal a.c. applications. Moreover, in combination with a switch starter, it can be made to produce the high voltage pulse needed to ignite the lamp (Fig. 32).

A practical choke ballast consists of a large number of windings of copper wire on a laminated iron core (Fig. 33). Heat losses, occurring through the ohmic resistance of the windings and hysteresis in the core, much depend upon the mechanical construction of the ballast and the diameter of the copper wire.

**Electronic ballasts**

Although more expensive, electronic ballasts - especially high-frequency types - offer important advantages over conventional choke ballasts, such as:

- Improved lamp and system efficacy
- No flicker or stroboscopic effects
- Instantaneous starting without the need for a separate starter
- Increased lamp life
- Excellent light-regulation possibilities
- No need for power-factor correction
- No hum or other noise
- Lower weight, especially for big lamp sizes
- Can also be used on d.c.

Fig. 32 Schematic diagram of a fluorescent lamp operated on a choke ballast in an a.c. starter circuit.

Fig. 33 Cut-away view of a choke ballast.
One basic design of electronic ballast involves a bridge rectifier to convert the mains voltage from a.c. to d.c. followed by a thyristor (chopper) regulator. The gate of the latter, which is connected in the lamp circuit, switches the thyristor on and off and so controls the lamp current. Sometimes the chopper output is connected to a low-frequency commutator to supply the lamp with a controlled, square-wave voltage to further improve the system efficiency (Fig. 34).

Another, and much more popular, approach is to rectify the current drawn from the mains supply and convert it into a high-frequency square-wave signal in the range 20 kHz to 100 kHz. For control of the lamp current, either an electronic stabilisation circuit or a conventional - but much smaller and therefore more efficient - choke ballast is used. In the latter case, light regulation is simply achieved by increasing the frequency. The Philips HF electronic ballasts are based upon this principle (Fig. 35).

For power-factor correction (see next Section), a filter needs to be incorporated between the mains and the electronic ballast. This can either take the form of an inductive coil or an electronic network. Whilst an electronic filter always forms an integral part of the ballast, the inductive filter coil is often supplied as a separate unit, and then strongly resembles an inductive ballast (see Fig. 36).
Electronic ballasts for compact fluorescent lamps (Fig. 37) handle so little power that they need no special power-factor correction filter.

In present-day lighting practice, it is still the inductive ballast that is employed in the great majority of installations, although high-frequency electronic ballasts are making big inroads, especially if light regulation is required. The higher cost of the electronic ballast long formed a barrier to its general use, but initial cost is more than offset by a higher system efficacy in the long run.

### 4.1.2 Power-factor correction

A capacitor and an inductor produce opposite phase shifts between current and voltage

An ideal capacitor will block a d.c. current but will allow an a.c. current to pass through it. In the case of a sinusoidal a.c. voltage, at the voltage peaks no current passes through the capacitor, the current reaching a maximum at the moment that the voltage passes through voltage zero. The result is a phase shift between current and voltage, the current leading the voltage by 90° (Fig. 38 left).

For an ideal inductor the opposite is true. This is a perfect conductor for a direct current, but a near open-circuit for an a.c. current, the current lagging 90° behind the voltage (Fig. 38 left).

The power factor

In practice, every electrical circuit contains both capacitive and inductive elements, which work in opposite directions, so the resulting phase shift will in fact always be less than 90°. This means that for a.c. circuits the relation

\[ P = V.I \]

for electrical power is no longer valid. Instead, this becomes

\[ P = V.I \cos \varphi \]

Fig. 38 In a capacitive circuit (left), the current (i) leads the voltage (V); in an inductive circuit (right) the current lags behind the voltage.
Fig. 39 Mono-compensation. The extra filter coil, which is sometimes necessary to prevent short-circuiting of high-frequency signals, is shown in broken lines.

Where \( \phi \) is the phase shift in degrees between voltage and current. \( \cos \phi \) is called the power factor of the circuit, and takes values between 0 and 1, corresponding to \( \phi = 90^\circ \) and \( \phi = 0^\circ \) respectively.

A low value of power factor is undesirable, because for the same power consumption a stronger current flows through the cables, wiring accessories and distribution equipment, with the result that the useful load that can be handled is reduced. Therefore, special tariffs and penalties may be imposed on the consumer taking a load with a low power factor. On the other hand, electricity suppliers may require that the \( \cos \phi \) of any installation exceeding a specified power consumption must be 0.85 or higher.

Power factor correction
In a fluorescent lighting installation employing only inductive ballasts, this figure cannot be reached. With an SL* lamp fitted with a conventional ballast, for example, the power factor is not higher than 0.5. Therefore, in any situation where more than just a few fluorescent lamps are used, some form of compensation has to be provided.

It might be thought that introducing a series or parallel capacitor to completely cancel out the phase shift produced by the choke would provide the answer. But such a circuit would have zero impedance and thus behave as an oscillator, which is certainly not what is wanted. Therefore, in practice, half of the lamps are run on capacitive ballasts (ballasts where the compensating capacitor has twice the impedance of the choke), and half are inductively ballasted without compensation. The lamp circuits are divided as equally as possible over the installation and over the three phases of the mains supply.

Two practical ways have been found of achieving this: mono-compensation and duo-compensation.

**Mono-compensation**
This consists of a capacitor in parallel with the lamp circuit. Typical capacitor values for a 50Hz mains are 4.2 \( \mu \)F for a 36 W or 40 W fluorescent lamp, and 6.5 \( \mu \)F for a 58 W or 65W lamp. In areas where high-frequency signals are sent through the mains – e.g. for switching purposes - a filter coil is placed in series with the capacitor to prevent these from being short-circuited (Fig. 39).

**Duo-compensation**
This is employed as the name suggests, for pairs of lamps, as for example in two-lamp luminaires. Here the capacitor is placed in series with one of the ballasts (Fig. 40).
In some countries, practically all multi-ramp luminaires have built-in duo-compensation for each pair of lamps (also called a ‘dual-lamp’ or ‘lead-lag’ circuit). Mono-compensation, on the other hand, is generally left to the installer, although there are also single-lamp luminaires available with the compensation built-in.

**Electronic ballasts**

An electronic ballast normally produces no phase shift, but nevertheless the power factor can take values lower than unity. This has to do with the difference in shape between the voltage and current waveform. Whilst the voltage waveform remains close to sinusoidal, the current drawn from the supply exhibits sharp peaks separated by prolonged periods when no current flows*) (see Fig. 41).

The result again is that the input power is less than the product of voltage and current. But the relationship between the three quantities is far more complex than in the case of phase shift, and power factor correction is impossible by inserting a simple capacitor in the circuit.

In electronic ballasts for larger fluorescent lamps (including all Philips TL'D HF electronic ballasts), a filter coil or electronic network is placed between the mains supply and the rectifier to shape the current waveform, but with compact fluorescent lamps with integrated gear this is scarcely possible for space and cost reasons. SL* lamps with electronic gear and PL*Electronic lamps therefore have a low power factor - of the order of 0.5 – which, in view of the low energy consumption, is considered acceptable by the electricity supply companies.

### 4.1.3 Series connection of lamps

Two lamps on a common ballast - the tandem circuit

In the dual-lamp circuit described above, each lamp has its own ballast. Under certain conditions, it is also possible to operate two lamps in series on a common ballast in a so-called tandem circuit (Fig. 42). A pre-requisite for such operation is that the sum of the operating voltages of

*) These peaks are due to the fact that large currents are drawn by the smoothing capacitor in the rectifying circuit at the moment that the voltage waveform approaches its maximum.

Fig. 41 The difference in waveform between the supply voltage (top) and the supply current (bottom) of a PL *E/C lamp results in a low power factor.

Fig. 42 Tandem circuit, with two lamps in series on a common ballast
the lamps is not higher than approximately 60 per cent of the supply voltage. This means that two lamps, each with an arc voltage of no more than 65 volts, can be connected in series via a common ballast to the 220/240 V mains. This restricts the maximum lamp length to 600 mm (2 ft), or the lamp power to 18/20 W (26 or 38 mm diameter lamps only). A tandem circuit is compensated using a series capacitor. Parallel connection of two lamps on a common ballast is impossible because of the negative resistance characteristic of the fluorescent lamp. All the current would flow through the lamp with the lower arc voltage.

4.2 Ignition

Starting aids

The internal resistance of a cold tubular fluorescent lamp is far too high for it to start automatically when the mains voltage is applied. Some sort of aid to starting is therefore needed to ignite the lamp. In practice, this involves one or more of the following solutions:

- preheating the electrodes to facilitate electron emission;
- providing an external conductor on or near the lamp tube, which is either floating, earthed or connected to one of the electrodes. The electric field so created facilitates the initial discharge. An alternative solution, which serves the same purpose, is the provision of an internal conductive coating on the tube wall.
- providing an internal auxiliary electrode in the form of one or two metallic strips along the inside of the tube;
- providing a voltage peak sufficiently high to initiate the discharge.

4.2.1 Preheat starter circuits

Fluorescent lamp circuits can generally be divided into those with and those without a separate starter. In starter circuits (Fig. 43), the electrodes are first preheated for a few seconds, after which a voltage peak is applied across the lamp to initiate the discharge. This process is controlled by an automatic switch - in combination with the ballast - which is called a ‘starter’.

Glow-discharge starters

A starter consists of two electrodes, at least one of which is bimetallic, enclosed in an argon/helium-filled glass bulb (Fig 44). A capacitor across the electrodes prevents radio interference caused by sparking. When the mains is switched on, a glow discharge starts between the electrodes, which is initiated by free electrons released by a small additive of a radio-active isotope, either tritium or krypton\(^{24}\).\(^{\text{(*)}}\)

\(^{(*)}\) Needless to say, the soft β-rays produced by these radio-active materials are absolutely harmless.

Fig. 43 Ballast, starter and compensating capacitor

Used in a starter circuit.

Fig. 44 Cut-away view of a glow-discharge starter.
The ignition process works as follows (Fig. 45):

The heat from the glow discharge causes the bimetallic electrodes to bend so that they make contact, completing the electric circuit and allowing the heating current to pass through the electrodes of the lamp. In the meanwhile, the discharge in the starter bulb has stopped, allowing the electrodes to cool down and so open. The opening of the contacts interrupts the rather heavy current flowing through the inductive ballast and the lamp electrodes, causing a voltage peak 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.

There are several types of glow-discharge starters, suited to different loads. Philips has the following:

- S2 for lamps with a maximum arc voltage of 60 V (18/20 W lamps);
- S10 for lamps with a maximum arc voltage of 100 V (58/65 W lamps);
- S11 for high-power solarium lamps (80/100 W lamps);
- S12 for high-power lamps operated on 220 V (115/140 W lamps);
- S16 for medium and high-power lamps operated on 240 V

Unless a separate preheating circuit is provided, two lamps in series, operated on a common ballast need two separate S2 starters (Fig. 42).

A normal glow-discharge starter will persist in trying to start a lamp that has become defective or has reached the end of its life. The result is a disagreeable lamp flicker and the eventual breakdown of the starter. Where this is considered unacceptable, a special type of glow-discharge starter (type SIS10) can be used—this will switch off automatically after a certain period of unsuccessful starting and can be reset, after lamp replacement, by pushing a button on the starter (Fig. 46).
Electronic starters

Apart from glow-discharge starters, there are also electronic starters. These supply both the preheating current and the starting pulse. Electronic starters make only one - very determined - start attempt, so that any flickering during the ignition phase is eliminated. Other advantages are that starting at low ambient temperatures is far more reliable and that lamp life is increased.

Philips has two types of electronic starters (Fig. 47), the ES08, which has four contacts, for preheating and starting, and the very compact S2-E and S10-E starters, which have two contacts to fit into a standard starter holder and which can be used as a direct replacement for glow-discharge starters.

In high-frequency electronic lamp circuits the starter function is incorporated in the ballast.

4.2.2 Preheat starterless circuits

Circuits for lamps with continuously heated electrodes

For reasons of simplicity and reliability, lamp circuits have been devised that do not employ a separate starter. These fall into two main groups, those with and those without provision for preheating the electrodes.

Any 38 mm fluorescent lamp of no longer than 1.2 metres (40 W) and with properly preheated electrodes will just start spontaneously on a mains voltage of 220/240 V under optimum ambient temperature conditions. However, to ensure that starting will be trouble-free under practical working conditions, preheat starterless lamps are operated in one of two circuits: the semi-resonant ballast circuit, or the non-resonant (or ‘rapid-start’) circuit.

Semi-resonant ballast circuit

By increasing the open-circuit voltage applied across the electrodes from 220 V to, say, 260 V or 280 V, reliable starting over a larger temperature range is obtained. The semi-resonant circuit in which this is achieved is shown in Fig. 48. It consists of a single choke ballast with an additional overwinding in opposition to the choke winding, and a series capacitor. When the circuit is switched on, the electrodes are preheated by a current through the series circuit (although sometimes a separate transformer is used), while the lamp current flows through the ballast alone. The lamp having started, the heating current continues to flow, but at a reduced rate.

By using special low-resistance electrodes, energy consumption is further reduced in this stage. An additional advantage of the semi-resonant ballast is that no separate power-factor compensation is necessary, the overwinding carrying a capacitive current which improves the overall power factor.
Rapid-start circuit

It is also possible to start preheat starterless lamps on 220 V in a normal (viz. non-resonant) ballast circuit, but then the temperature range over which reliable starting is possible becomes rather narrow. To facilitate the ignition process as much as possible, preheat starterless lamps used in these so-called rapid-start circuits are often provided with an internal conductive coating or a conductive strip on the outside of the tube (Fig. 49). The conductor is connected to one of the electrodes (via a 1 MΩ resistor in the case of an external strip to prevent accidents when touching the strip of an operating lamp). Philips ‘TL’M rapid-start lamps are fitted with such an external strip. These and other lamps intended for use in startless circuits are also provided with an external silicone coating to prevent starting problems in humid surroundings.

Lamps not provided with a starting conductor - such as the Philips ‘TL’RS types - must be mounted no more than two centimetres from an earthed metal conductor, which can be a part of the luminaire.

In rapid-start circuits, the preheating current for the electrodes is generally provided by a separate transformer or from secondary windings wound, transformer-wise, over the ballast (Figs 50 and 51).

Sequence start

Two 20 W starterless lamps in a rapid-start circuit can be operated in series on the 220/240 V mains with a common ballast (see also Section 4.1.3). It is, however, necessary that a provision is made that they start one after the other, which can be done by adding an auxiliary capacitor in parallel with the first lamp. This is called a ‘sequence-start circuit’ (Fig. 52).
4.2.3 Cold-start circuits

Cold-start lamps need heavy-duty electrodes

Ignition is more difficult with cold than with heated electrodes. Furthermore, the electrodes have to be more robust, as the emitter material is easily scattered when electrons are torn from the cold cathode.

There are, in fact, two ways of ensuring reliable cold starting. The first is to use a very large ballast to produce an extra-high-voltage pulse, sufficient to start a cold lamp. But a bulky and expensive ballast is unnecessary for stable operation, so wherever possible two lamps are run in series on one ballast and provided with a circuit to start them one after the other (‘sequence start’, see Fig. 53). This arrangement is particularly popular in countries with a 110 / 127 V mains voltage.

Lamps with an internal conductive strip

However, the most common way of ensuring reliable cold starting is to make provisions for easy starting in the lamp itself. This is achieved by employing an auxiliary electrode in the form of a conductive strip running along the inside of the tube (Fig. 54). One end of the strip is connected to one of the electrodes, the other end reaching close to the other electrode.

When the lamp is switched on, a glow discharge occurs between this auxiliary electrode and the opposite main electrode. This releases enough free electrons to start the main discharge. As the resistance of the discharge path is much lower than that of the metallic strip, the glow discharge ceases once the lamp is operating.

The auxiliary electrode is employed, for example, in the Philips ‘TL’S and ‘TL’X cold-start fluorescent lamps. These can therefore be operated on ordinary ballasts as used with switch-start lamps of the same power rating (Fig. 55). Because they start without any appreciable delay or flicker after switching-on, cold-start lamps are often referred to ‘instant-start’ lamps.
4.2.4 Run-up

After ignition, it takes two or three minutes before the mercury vapour in the fluorescent lamp has reached its working pressure. During this period, the luminous flux gradually increases to a maximum. However, as the initial flux is about 60 per cent of the final value, this increase will not normally be noticeable.

Amalgam lamps have more or less the same run-up time, but here the initial luminous flux is only some 20 per cent of the maximum (Fig. 56). The use of these lamps is therefore not recommended if operating periods are very short or where switching is frequent.

4.2.5 Re-Ignition

When the lamp is switched off, the vapour pressure drops so quickly that instantaneous re-ignition will seldom, if ever, pose any problems. Starterless lamps in special circuits can even be flashed on and off, a feature that finds use in advertising signs.

4.3 Non-standard operating modes

4.3.1 Operation on 110/127 volts a.c. supply

Many parts of the world, notably North and Central America and the Far East, have public mains supplies with voltages ranging from 100 V to 127 V. With such a low voltage, the requirement that the supply voltage should be at least 70 per cent higher than the lamp voltage to guarantee stable operation clearly cannot always be met. For this reason, the larger diameter (38 mm or even 54 mm) lamps with their lower operating voltage, and power ratings not exceeding 40 W, are generally used. ‘Retrofit’ lamps (comparable to the 26 mm ‘TL’D lamps in 220/240 V regions) are mostly of 32 mm diameter (T10, see also Section 2.1).

Higher wattage lamps can, however, be operated on this voltage, provided a step-up transformer is used. This generally takes the form of an auto-leakage transformer, which
doubles as a ballast, and also provides the heating current to the electrodes. Lamps operated in this mode are almost invariably of the (preheated) starterless type (Fig. 57 left).

In those parts of the world where 110/127 V networks form the exception rather than the rule, separate step-up transformers in combination with 220 V ballast/starter circuits are normally used (Fig. 57 right).

SL* lamps for 110/127 V mains either have a special electronic ballast and starter circuit incorporated in the lamp, or employ a larger diameter discharge tube - to reduce the lamp voltage - in combination with a conventional choke ballast and glow-discharge starter (see also Section 6.4.1). The latter solution is also used for some PL types (see Fig. 58).

### 4.32 Operation on d.c. supply

Since the advent of small and inexpensive solid-state d.c./a.c. inverters, the operation of fluorescent lamps direct form d.c. supplies is becoming increasingly more rare, but may still be found occasionally in electric public-transport vehicles or on board of ships.

**High-voltage d.c.**

Fluorescent lamps can be operated on d.c. voltages of 70 V and above when

Fluorescent lamps of special construction and using special gear can be operated on d.c. supplies of approximately 70 V and above. The main difference between a.c. and d.c. operation is that with the after an ohmic resistor instead of a choke has to be used as a ballast (although a choke is sometimes added to the circuit to provide a starting pulse when the lamp is switched on, see Fig. 59). Tungsten-filament lamps (either conventional or specially designed types), with their strong positive temperature coefficient of resistance, are almost universally used as current-limiting devices for fluorescent lamps operated on d.c.
For supply voltages not exceeding 100 V the electrodes are sometimes preheated. Generally speaking, however, d.c. lamps are of the cold-start type. To facilitate ignition, auxiliary electrodes in the form of internal conductive strips are normally employed. Two strips are always needed, one connected to each main electrode, for the strip can only serve as the anode. If the supply voltage is higher than 200 V, two or more lamps are often connected in series and started one after the other using an electrical relay (Fig. 60).

Electrophoresis

A typical problem, which only arises with d.c. operation, is that of 'electrophoresis'. During operation, the mercury in the discharge migrates from the positive to the negative electrode. The result is that a dark zone spreads from the positive electrode, which produces a rapid fall-off in light output. To prevent this from happening, the polarity of the lamp must be reversed at regular periods, e.g. every four hours.

Low-voltage d.c.

Operation of fluorescent lamps on low-voltage d.c. supplies as for example delivered by batteries, requires the use of inverters (Fig. 61). These generally convert the d.c. voltage into a high-frequency a.c. voltage, which is stepped up by a transformer to the required lamp voltage. Current regulation is either done electronically at the input of the inverter or by a separate choice in the lamp circuit.

4.3.3 Operation under adverse environmental conditions

Special lamps, luminaires and electrical circuits have been developed for use in hot, cold, humid or potentially explosive environments.

High ambient temperatures

Amalgam lamps - and to a lesser extent krypton-filled ('TL'D) lamps as well - are not susceptible to the drop in light output at high ambient temperatures experienced by normal fluorescents. Where normal lamps are operated on inductive ballasts, these may well overheat due to the increase in the lamp current brought about by the higher operating temperature.

However, where the decrease in light output and luminous efficacy can be tolerated, and provided that proper measures are taken to prevent overheating of the circuitry, tube wall temperatures of up to about 90°C are acceptable.

The use of properly ventilated luminaires will, in most environments, obviate any heat problems. An airstream through the luminaire is an effective way of removing the heat generated by the lamp and ballast.
Low ambient temperatures
Here there are two problems to be considered: difficult lamp starting, and unsatisfactory lamp performance, which is evidenced by a sharp fall off in both light output and luminous efficacy. Under extreme conditions, the lamp may even extinguish.

Facilitating starting
Starting at very low temperatures is facilitated by preheating the electrodes and by providing a high-voltage ignition peak. Some manufacturers produce special lamps for use at low temperatures. These have a lower than normal gas pressure to aid starting, but as a consequence of this have a shorter operating life.

Ensuring reliable performance
The best way to ensure good, reliable performance at very low temperatures is to conserve the heat generated by the lamp itself. This can be done by using all-enclosed well-insulated luminaires, or by employing special lamps having an outer jacket of clear glass (Fig. 62). There are also lamps having a very high wall loading, designed specifically for use at low temperatures only.

Humid conditions
Humid operating conditions can also give rise to problems with lamp starting. Lamps provided with a water-repellent silicone coating are available, which are trouble-free in this respect.

Special lamps exist for use in these hazardous areas
The lamps used in hazardous areas where there is risk of explosion must satisfy two very important requirements. In the first place, even in the case of breakage, the lamp construction must be such that no heated surface becomes exposed. Secondly, there must be no exposed electrical connections that might produce sparks.

The first requirement is met by using cold-start lamps, the second by using special caps and holders, the electrical contact surfaces of which are comparatively large or completely enclosed in small explosion-proof chambers, or both. Philips “TL’X lamps have been specially designed to meet both these requirements.

4.4 Dimming
Present-day dimming equipment for fluorescent lamps is either of the thyristor (chopper) type or of the variable frequency type (HF electronic light regulation). Both have been described in Lesson 7, Section 3.5.

Dimming to give half the output is nearly always possible
By using thyristor dimmers, practically any type of fluorescent lamp can be light dimmed down to about 50% of the nominal lamp current, which roughly corresponds to a 50 per cent reduction in light output (so-called “top dimming”)\(^*)\). For indoor installations, however, top dimming is of limited practical use.

\(^*)\) At ambient temperatures below 5°C krypton-filled lamps, like the Philips “TL’D, may become unstable when dimmed.
The disadvantage of thyristor dimming where lamp circuits incorporating glow-discharge starters are concerned, is that the dimmed lamp will cause the starter to become conductive. At what degree of dimming this will happen is difficult to predict, but the result is that the starter will make repeated attempts to ignite the lamp. This is the chief reason why dimming of ‘TL’ fluorescent lamps in a glow-discharge starter circuit is discouraged.

**Dimming down to zero calls for continuously heated electrodes**

Below 50% of the nominal lamp current, the discharge will no longer provide sufficient heat to keep the electrodes at the proper emission temperature and continuous electrode heating becomes necessary. The heating current must be independent of the lamp current, thus a separate heating transformer will be required. Lamps operated in this mode can be dimmed to give almost zero light output (but not entirely, unless a switch is provided). They can also be started from a dimmed position. These dimming installations almost invariably operate at high frequency to prevent disturbing flicker at low lighting levels.

**Dimming by varying the supply frequency**

With the Philips HF electronic light regulation ballast the lamp current can be regulated down to about 10% of the nominal value. Dimming is here achieved by increasing the frequency of the supply current.

The lamp circuit of the Philips HF electronic light regulation ballast is shown in Fig. 63. Increasing the frequency of the square-wave voltage waveform applied across the lamp circuit causes the impedance of the choke L to increase and that of the capacitor C₁ to fall. The current through the lamp therefore decreases while the proportion of the circuit current flowing through C₁ - the electrode heating current - increases. The electrodes are thus kept at the proper emission temperature. The circuit has been so dimensioned that at the lowest dimming position (lamp current 10 per cent of the nominal value), the total current through the circuit has dropped to approximately 30 per cent of its nominal value.

A lamp operated on the HF electronic light regulation ballast is started on the nominal operating voltage and frequency. Immediately after the lamp has ignited, it is automatically adjusted to the preset dimming level. This happens so fast as to be unnoticeable.

**4.5 Flicker and interference**

**4.5.1 Flicker**

The flicker produced by a fluorescent lamp operated on a 50 Hz sinusoidal mains supply will only become noticeable in exceptional cases. However if the lamp current is severely distorted (high peak factor), an objectionable degree of flicker may occur, especially at the ends of the lamp. Thyristor dimming may also produce disturbing flicker as the dark period of the cycle increases. Finally, the use of phosphors exhibiting little or no afterglow may result in a more pronounced flicker.

Measures to counteract the effect of flicker have been described in Lesson 7, Section 3.6.

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Fig. 63 Schematic diagram of the Philips HF electronic light regulation ballast.
4.5.2 Interference

Radio interference

Fluorescent lamps produce weak radio signals, especially toward the end of their life. Under exceptional circumstances, these signals may become audible as a 100 Hz hum on radio AM bands, although the manufacturer at the control gear (or the person installing it) will most probably already have taken steps to ensure that such interference is kept to the absolute minimum. This involves fitting small parallel capacitors at critical places, for example in the starter. A solution may also be found in relocating the aerial.

Audible hum

The iron core of an inductive ballast produces mechanical vibrations, which in quiet surroundings may become audible as a low-pitched hum. The hum will be more pronounced if the ballast is mounted on a resonant surface. Relocating the ballast or making the mounting surface more rigid will eliminate this problem.
5. Principal fluorescent lamp types

5.1 Preheat starter lamps

Preheat starter lamps form by far the largest single lamp category, at least in countries having a 220/240 V mains supply. These lamps need a preheating circuit for the electrodes and a glow-discharge or electronic starter. Several types can be distinguished (the Philips designation is given in brackets):

**Standard** (‘TL’) lamps are the fluorescent version of incandescent GLS lamps. They have diameters of 26 mm (T8) or 38 mm (T12) - within North America 32 mm (T10) and sometimes, 54 mm (T17) as well. Lamp wattages range from about 20 W to 125 W.

**‘Retrofit’** (‘TL’D) lamps are energy-saving 26 mm lamps intended to replace 38 mm lamps of approximately the same luminous flux in existing installations (Fig. 64). Krypton has been added to the fill gas in order to maintain the same operating voltage in spite of the smaller tube diameter. Lamp wattages range from 18 W to 58 W.

**High-frequency** (‘TL’D HF) lamps are specially designed for operation on HF electronic ballasts. The Philips execution resembles the 26 mm ‘TL’D retrofit lamp, but the electrodes are lighter, and the inert gas is a neon-argon mixture, instead of krypton. Lamp wattages range from 16 W to 60 W.

**Miniature** (‘TL’) lamps (Fig. 65) have a diameter of 16 mm (T5). Lamp wattages range from 4 W to 13 W.

**High-output** (‘TL’ or ‘TL’K) lamps have a higher power dissipation and luminous flux than would be expected from their length and diameter. As a consequence of this, their operating temperature is also higher, and ‘cool spots’ have had to be added to limit the mercury vapour pressure (see Section 3.2). High-load lamp wattages range from about 115 W to 215 W.

**Special** lamps. These can be grouped as follows:

**Special shapes**, for example: circular (‘TL’E), U-shaped (‘TL’U) and W-shaped lamps (Fig. 66). Circular lamps are provided with a special four-pin cap.

**Special lighting tasks**, for example: lamps colour —/79 for displayed meat, lamps colour —/89 for aquaria.
Coloured (‘TL’) lamps employ special fluorescent powders, sometimes in combination with a pigment coating to filter out unwanted wavelengths. They are mainly used in decorative applications. The Philips colour designation of these lamps is:
—/15 for red  —/16 for yellow  —/17 for green  —/18 for blue

Reflector (‘TL’F) and aperture lamps have a white reflecting layer underneath the fluorescent coating over part of the circumference. The ‘window’ of a typical reflector lamp extends over 160°, while for an aperture lamp, this angle is 30° – 60°. Reflector lamps find application where the use of external reflectors is impossible or impracticable, and also in very dirty surroundings, as dust settling on top of the lamp will cause little or no light loss. They are also available in the form of miniature lamps.

It is important that the lamp always fits into the luminaire with the reflector in the right position. To ensure this, two versions of the same lamp are available, with the reflector parallel to the plane through the contacts or perpendicular to it (Fig. 67). Aperture lamps are mainly used in special applications where a high luminous intensity is required, such as in signal lighting and in copying machines.

Unusual ambient temperature lamps. Lamps for use in very high temperatures employ an amalgam filling, while for very low temperatures a lower gas pressure (to facilitate starting) or an insulating glass jacket to conserve the heat from the discharge, or both, are employed.

D.C. (‘TL’C) lamps with heated electrodes are fundamentally the same as their a.c. counterparts, but often employ auxiliary electrodes (always two, see Section 4.3.2) to facilitate starting. Of course, special gear is needed for d.c. operation.
5.2 Preheat starterless lamps

Rapid-start lamps

These are referred to by Philips as rapid start (RS) lamps. They differ only on a few points from the previous category and indeed, can also be used in starter circuits.

In lamps intended for use in starterless circuits special measures have been taken to ensure reliable starting. These include an external silicone coating, an internal conductive layer or an external conductive strip (see Section 4.2.2).

Philips produces three types of (38 mm) rapid-start lamps. 'TL' (RS) with 3-volt electrodes and an external silicone coating;
'TL'M (RS) as 'TL' (RS), but provided with an additional external conductive strip;
'TL'A with 8-volt electrodes for operation on 240 V mains supply (chiefly in the UK).

Of course, most of the special types described in the previous section are also available in a rapid-start version, such as circular and reflector types.

5.3 Cold-start lamps

Instant-start lamps

Cold-start lamps have special, rugged electrodes and often employ some form of starting aid, generally an auxiliary electrode. As these lamps ignite almost instantaneously at switch-on, they are often referred to as instant-start lamps.

The gap between the auxiliary electrode and the opposite main electrode is small enough to allow the other contact to become live if one contact is inserted into the lamp holder. For this reason, these lamps are generally provided with special recessed lamp caps (R18s).

Philips manufactures the following types of cold-start lamps (Figs 68 and 69):

'TL' Slimline without starting aid, intended for operation on a heavy-duty ballast (USA only);
'TL'S provided with an auxiliary electrode and recessed contacts;
'TL'R provided with two auxiliary electrodes for operation on d.c.;
'TL'X provided with special caps for use in potentially explosive environments.
6. Compact fluorescent lamps

6.1 Introduction

Compact fluorescent lamps have been developed for use in those applications that were traditionally the province of incandescent lamps. At present, four basic forms of compact lamps can be distinguished:

- A conventional 26 mm or 38 mm fluorescent tube, generally bent into a circle and fitted with an integral ballast and starter, and given a standard screw or bayonet cap (Fig. 70).
- A single small-bore tube folded into a flat compact form, or two or more parallel small-bore tubes interconnected in such a way as to offer a continuous pathway for the electric discharge (Fig. 71). The lamp is provided with a starter and either a conventional or an electronic ballast, and a screw or bayonet cap. The Philips PL*E/C and PL*E/T lamps belong to this category.
- A small-bore fluorescent tube folded into a compact form and placed in a glass or plastic outer envelope (Fig. 72). Integral with the lamp are a starter and a conventional or electronic ballast, and the whole is fitted with a screw or bayonet cap. Sometimes, lamp and luminaire form an integral and inseparable unit. The Philips SL* lamps belong to this category.
- Two or more parallel small-bore tubes, interconnected near or at the ends in such a way as to offer a continuous pathway for the electric discharge (Fig. 73). The lamp is fitted with a single special cap that sometimes contains a starter. The Philips FL lamps fall into this category.

Fig. 70 standard-diameter, single-ended fluorescent lamps with integral gear and screw cap. The example in the right was made by Philips in 1945.

Fig. 71 small-bore, single-ended fluorescent lamps with integral gear and screw cap.

Fig. 72 Small-bore, single-ended fluorescent lamps with separate ballast and special cap.

Fig. 73 Small-bore, single-ended fluorescent lamps with outer envelope, integral gear and screw cap.
6.2 Construction

**All compact fluorescents employ narrow-band phosphors**

The compact construction of the SL* and PL types of lamps calls for a shorter tube length and a smaller tube diameter than is found in conventional fluorescent lamps of the same luminous flux (Figs 74 and 75). The result is that the wall loading in these lamps is considerably higher than in a conventional tubular fluorescent lamp. The main problem in the development of the compact lamp, therefore, was to find a fluorescent material that would be more resistant than the traditional halophosphates to the higher density UV-radiation. The answer was found in the more stable narrow-band phosphors, as used in three-band fluorescent lamps of the 80-series.

**Ways to keep the mercury vapour pressure down**

Another problem was the higher operating temperature generally encountered in highly-loaded lamps. The solution adopted in the Philips PL-S, PL-L, PL-C and PL*E/C lamps was to extend the parallel tubes some one centimetre beyond the point of interconnection. The dead ends form cool spots, which keep the mercury vapour pressure down. In the case of the SL*, PL-T and PL*E/T lamps, which have no provision for cool spots, the solution was to fill the discharge tube with amalgam instead of pure mercury, thus ensuring efficient operation at higher temperatures.

*Fig. 74 Stages in the assembly of an SL* compact fluorescent lamp.*

*Fig. 75 Stages in the assembly of a PL-S compact fluorescent lamp with integrated starter and separate ballast.*
6.3 Lamp circuits

Compact fluorescent lamps are operated on a wide variety of built-in or external control gear. The following operating modes can be distinguished:

- with a built-in choke ballast and glow-discharge starter (Philips SL*, SL*D and SL*Agro lamps);
- with built-in electronic gear (Philips SL*DE, PL*Electronic/C and PL*Electronic/T lamps);
- with built-in glow-discharge starter for an external choke ballast (Philips PL-S/2p, PL-C/2p and PL-T/2p lamps);

Compact fluorescent lamps with built-in electronic gear (SL*DE and PL*Electronic lamps) cannot be dimmed. The dimming of SL* and PL lamps with a built-in glow-discharge starter is strongly discouraged for the reasons outlined in Section 4.4.

6.4 Compact fluorescent lamp types

6.4.1 Screw or bayonet caps

**SL* and PLC*E lamps**

These lamps consist of a standard or small-bore fluorescent tube, bent or folded into a compact form and provided with integrated gear and a screw or bayonet cap for replacement of incandescent lamps in existing installations. The gear consists either of a miniature choke ballast and a glow-discharge starter, or else is fully electronic. In a number of cases the discharge tube is encapsulated in an outer envelope, which resembles the bulb of an incandescent lamp. Lamp wattages are such as to provide the same luminous flux as the incandescent lamps they replace.

The Philips range comprises four main types, one with a cylindrical outer envelope, one with a globular outer envelope, and two without an outer envelope, with straight or curved tubes.

**Cylindrical SL* lamps**

These have a corrugated outer envelope (‘Prismatic’) or an opal one (‘Comfort’), and are fitted with an E26/E27 screw or B22 bayonet cap (Fig. 76). The filling is amalgam, and three-band phosphors are used. Two light colours are available, SL* and SL* Daylight (the latter only in the ‘Prismatic’ version), corresponding to the colours 82 and 85 of tubular fluorescent lamps.

Lamps for 220/240 V have a built-in choke ballast and glow-discharge starter. The version for 110/127 V is available with either the same type or electronic gear (referred to as ‘Magnetic’ or ‘Electronic’, respectively).


*Fig. 76 Cylindrical SL* lamps. From left to right: 18 W opal electronic (for 110/127 V mains), 18 W opal (‘Comfort’) and 13 W clear (‘Prismatic’).*
Globular SL* lamps
There are five types at globular lamps to suit different applications (Fig. 77). With the exception of the SL*D 18 W, all types are made for operation on 220/240 V mains supply only.

SL* Decor (SL*D). These are similar to standard SL* lamps, but have a globular opal outer bulb. The light colour corresponds to the colour 82 of tubular fluorescent lamps (2700 K).
Wattage ratings: 9W, 13 W and 18 W, for 220/240V, or 18 W only for 110/127 V, including ballast losses.

SL* Decor Electronics (SL*DE). This is a version of the SL* Decor with electronic gear. Wattage ratings: 11 W, 15 W and 20 W including ballast losses.

SL* Agro (SL*R). This is a globular SL* lamp with conventional gear, fitted with a transparent outer bulb and internal reflector. It is chiefly used for plant lighting in greenhouses. Wattage rating: 18 W, including ballast losses.

PL* Electronic lamps
These consist of four straight or three curved interconnected parallel narrow-bore tubes, and are fitted with electronic gear and a screw or bayonet cap.

P1* Electronic/C. These consist of four interconnected parallel tubes. The interconnections are at the bottom and about one centimetre below the top, the ‘dead’ ends providing cool spots. PL*E/C lamps have no outer envelope. They are fitted with electronic gear and an E14 or E27 screw or B22 bayonet cap (Fig. 78). PL*E/C lamps are made for operation on 220/240 V only, and are available in two light colours, normal and ‘Daylight’, corresponding to the colours 82 and 85 of tubular fluorescent lamps.

PL*Electronic/T. These consist of three interconnected folded parallel tubes. The filling is amalgam, as there is no provision for cold spots. PL*E/T lamps have no outer envelope and are fitted with electronics gear and an E27 screw or B22 bayonet cap (Fig. 79 right). The lamps are made for operation on 220/240 V only, and are available in two light colours, normal and ‘Daylight’, corresponding to the colours 82 and 85 of tubular fluorescent lamps.
Wattage ratings : 15 W, 20 W and 23 W, including ballast losses.
PL* Electronic/D. These are identical to PL*E/T lamps, but fitted with an opal, globular outer bulb (Fig. 79 left). Available in colour 82 only. Wattage ratings: 15 W, 20 W and 23 W, including ballast losses.

6.4.2 Special caps

PL lamps

The lamps fitted with special caps are intended for use in compact luminaires. They always need a separate choke or electronic ballast, but sometimes the starter is built in.

Philips manufactures the following types (Fig. 80).

PL-S lamps. These consist of two parallel tubes of 12.5 mm diameter, bridged just below the top to provide cool spots. They employ three-band phosphors. Three light colours are available, corresponding to colours 82, 83 and 64 of tubular fluorescent lamps. PL-S lamps have either a two-pin or a four-pin cap. Those with a two-pin cap are designated ‘2p’. They require a separate ballast, but have a small glow-discharge starter incorporated in the base, and a capacitor to guard against radio interference. Lamps with a four-pin cap are
principally for use with electronic gear, but can also be operated on a conventional ballast and starter circuit. These lamps carry the additional designation ‘4p’.
Wattage ratings for both types (not including ballast losses): 5 W, 7 W and 9 W for both 110/127 V and 220/240 V; 11 W for 220/240 V only; 13 W for 110/127 V only.

**PL-C lamps.** These are basically the same as PL-S lamps, but comprise four parallel tubes, bridged near the top and bottom so as to offer a continuous pathway for the discharge. They are also available in colours 82, 83 and 84, and provided either with a two-pin cap with integrated starter (designated ‘2p’), or with a four-pin cap (designated ‘4p’).
The latter type is principally intended for use with electronic gear, but can also be operated on a conventional ballast and starter circuit. Lamps for operation on 110/127 V have tubes of 17.5 mm diameter, instead of 12.5 mm, to obtain a lower lamp voltage, and are designated PL-CL. (see Fig. 48). These exist with two pins only.

**PL-T lamps.** These consist of three interconnected folded parallel tubes (Fig. 81). The filling is amalgam, as there is no provision for cold spots, which results in a somewhat slower run-up. PL-T lamps are available in colours 82, 83 and 84. They are provided with either a two-pin cap and integrated starter (designated ‘2p’) or with a four-pin cap for operation on electronic gear or a conventional ballast and starter circuit (designated ‘4p’).
Wattage ratings: 18 W, 26 W (two and low-pin versions) and 32 W (four-pin only).

**PL-L lamps.** This is a larger version of the PL-S type, with tubes of 17.5 mm diameter, and is available in colours 82, 83, 84, 94 and 95. PL-L lamps are always provided with a four-pin cap, and require a separate ballast and starter, or electronic gear.

*) In the two-pin version only.

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*Fig. 81 PL-T lamps. 32 W/4p (left) and 18 W/2p (right).*
7. Small-diameter fluorescent lamps

7.1 Introduction

Fluorescent lamps are normally intended for operation on a voltage not exceeding the mains voltage. This determines the minimum diameter, or rather the diameter-to-length ratio, because, leaving other parameters - as the type and pressure of the buffer gas - the same, the arc voltage increases with reduction of the diameter of the tube (Fig. 82). In very narrow tubes the arc voltage would rise too high for stable operation on 100/127 or 220/240 volts. This is the reason why standard fluorescent lamps have a diameter of 38 or 26 mm, and even the relatively short miniature and compact fluorescent lamps are still of 16 or 12.5 mm diameter.

Thus, any attempt to reduce the diameter of the lamp will result in an increase of the arc voltage but otherwise electrical and lighting characteristics will not change very much, so that small diameter fluorescent lamps are a feasible proposition, provided a suitable high-voltage supply is available.

7.2 Construction

T5 and T2 lamps are constructed as conventional tubular fluorescent lamps, with heated, coiled-filament electrodes. The very narrow T1 lamps, however, are fitted with hollow...
cylindrical electrodes of chrome-nickel iron (Fig. 85). The electrodes are sometimes, but not always, coated with emitter material. The filling consists of a neon-argon mixture and some milligrams of liquid mercury. Both the rare-gas mixture and the mercury vapour have a working pressure that is higher than in normal fluorescent lamps\(^*\)), which implies that the cold-spot temperature must also be higher (up to 70°C in T1 lamps, see also Section 4.2). The tube is coated at the inside with three-band phosphors of the same type as used in ‘TL’ fluorescent lamps of the 80-series.

Without exception, small-diameter fluorescent lamps are operated on high-frequency electronic ballasts (Fig. 86). Sometimes, the high-voltage transformer forms a separate unit.

### 7.3 Performance

Apart from the higher arc voltage, performance is hardly influenced by the diameter.

Taking a tube length of one metre as an example, the arc voltage will be approximately 150 volts for a T5 lamp, 250 volts for a T2 lamp and 1000 volts for a T1 lamp.

Because of the low working temperature of the unheated electrodes (approximately 200°C), the voltage drop at the cathode of a T1 lamp is approximately 150 volts, compared with 10 volts for a standard fluorescent lamp with electrode temperatures of approximately 1000°C. However, the relation between cathode fall and total lamp voltage is in both cases practically the same, so that, for lamps of the same length, the luminous efficacy remains comparable with

\(^*\) In the case of tubular fluorescent lamps, the product of the diameter of the tube and the gas and mercury vapour pressure is an almost constant factor.
that of a standard lamp, namely about 75 lumens per watt for a one-metre T1-lamp. The same applies to colour characteristics, lamp life and depreciation.

T5 lamps even more closely match the performance characteristics of standard fluorescent lamps with a luminous efficacy of approximately 100 lumens per watt.

7.4 Lamp types and applications

Display lighting, edge lighting and backlighting

Only a few types of small-diameter fluorescent lamps have yet appeared on the market (1994). Straight T2 lamps of up to 13 watts are used for local lighting tasks as the illumination of paintings, shelves, display cases, etc. (Fig. 87). Furthermore, they are used for the edge lighting of glass shelves, orientation and emergency glass signs and LCD screens (Fig. 88). T1 lamps, bent into a U-form or zigzag-folded (Fig. 89), are used for flat, decorative wall luminaires, orientation and emergency luminaires, and the backlighting of LCD computer displays and television screens. Philips manufactures a type especially for the backlighting of LCD television screens, with a colour temperature of 8700 K (Fig. 90). This lamp has a tube diameter of only 4 millimetres which makes it one of the flattest light sources on the market but straight lamps for edge lighting already exist with an internal diameter of only 2 millimetres.
8. Fluorescent induction lamps

8.1 Introduction

Fluorescent induction lamps are radio-wave excited lamps working on the low-pressure mercury discharge principle (Fig. 91). A high-frequency electromagnetic field is generated in the discharge vessel by inductive coupling via an antenna coil. The high-frequency supply power signal is produced by an electronic oscillator circuit. Because the discharge does not take place between two electrodes - as is the case with all other discharge lamp types – induction lamps are classified as ‘electrodeless lamps’ and as such form one of the types described in Lesson 14, Section 6. As the lamp life of discharge lamps is generally limited by the wear-down of the electrodes, longevity is a characteristic feature of electrodeless fluorescent induction lamps.

8.2 General construction and working

All fluorescent induction lamps are characterised by the following three main parts (Fig. 92):

- h.f. power generator
- antenna
- discharge bulb

Fig. 91 The prototype of the first induction lamp was presented as long ago as 1976.

Fig. 92 Working principle of the fluorescent induction lamp.
Internal or external antenna

The antenna is basically an induction coil, which generates a high-frequency electromagnetic field in the discharge vessel. The normal position of the antenna coil is in a cylindrical cavity inside the bulb. This arrangement has the advantage of the most efficient inductive coupling with the plasma\(^*\), combined with minimal stray radiation. The main drawback is that much attention has to be paid to the removal of the excess heat generated in the antenna coil. Therefore, at least one manufacturer has opted for a coil around the outside of the discharge vessel (Fig. 94). This makes the construction of both the power coupler and the bulb simpler. At the same time, however, this solution requires the lamp being seated into an extensively screened luminaire, even including a wire-mesh cover over the light window, to comply with international requirements with respect to suppression of stray radiation (Fig. 95).

The discharge bulb is an all-glass vessel, filled with an inert gas mixture under low pressure and a small dose of mercury or mercury amalgam. The inside of the vessel is coated with a fluorescent powder, or a mixture of fluorescent powders, of the same type as used in normal tubular fluorescent lamps.

Prevention against stray radiation

Sometimes, the discharge vessel is given a surface treatment to prevent electromagnetic radiation from the antenna coil leaving the bulb. This can be in the form of an internal conductive coating (see Section 2.2.2) or external conductive metallic strips, or both. If these preventive measures are not incorporated in the lamp, they must be built into the luminaire, in the form of metal screening.

\(^*\) A plasma is an ionised gas.
8.3 Construction and working of the Philips QL lamps

8.3.1 Construction

Three separate parts

In the Philips QL lamp system, the power generator, antenna and discharge vessel are constructed as separate units (Fig. 96).

The high-frequency power generator is encased in an all-metal housing. The electronic circuitry must be constructed to the highest professional standards, so as to ensure that the lifetime matches the rated life of the bulb (Fig. 97).

A coaxial cable connects the h.f. generator to the antenna which, together with the heat removal rod and the mounting flange, form the so-called power coupler. The length of the cable is critical, as it forms part of tuned load on the h.f. generator. The power coupler assembly is located in a cylindrical glass cavity inside the discharge vessel. The part forming the antenna is essentially an induction coil wound around a core of ferrite (a ceramic material with ferromagnetic properties). The coil is overwound with a counter winding in which an electromotive force in counterphase with the input voltage is generated (Fig. 98). This provides an effective protection against electric stray fields.
The importance of heat removal

Despite the efficiency of the inductive power coupling, much heat is generated in the antenna coil, which is aggravated because of its location inside the lamp. In order to prevent temperatures rising to over 250°C, an effective heat-removal device is necessary. This takes the form of a heat-conducting metal rod inside the ferrite core of the power coupler (Fig. 99). The rod is attached to the mounting flange, which doubles as a cooling fin and has to be mounted on a metal plate forming part of the luminaire.

The bulb filling differs somewhat from normal fluorescent lamps

The pear-shaped discharge vessel is filled with argon at a very low pressure (30 to 60 Pa, compared with 2500 Pa for a tubular fluorescent lamp), to which some krypton has been added to facilitate ignition. Mercury is present in the form of amalgam, which is necessary because of the relatively high operating temperature of the lamp (see Section 2.4.3). In addition to the main amalgam, which governs the steady operation of the lamp, an auxiliary amalgam capsule is employed in the Philips QL lamps to accelerate the running-up process (Fig. 100).

Three-band phosphors

The inside of the discharge vessel is coated with a fluorescent layer, which is of the same composition as the phosphor mixture found in 80-series three band fluorescent lamps (see Section 2.2.1). Between the bulb wall and the fluorescent layer, there is a transparent coating of silica as a protection against excessive mercury absorption by the glass during the long life of the lamp.

Lamp and luminaire form an Integral unit

In most cases, the QL lamp system and the luminaire are supplied as an almost inseparable unit by the luminaire manufacturer (Fig. 101). This not only guarantees adequate protection of the system during its long life and adequate screening against stray radiation, but also minimises light depreciation as a result of pollution of the interior surfaces.
8.3.2 Steady operation

The r.f. power signal

The high-frequency power signal is generated by an oscillator circuit at a frequency of 2.65 MHz. This frequency not only guarantees the most efficient power coupling to the discharge vessel but also has the advantage of not being occupied by normal broadcast bands, which reduces the risk of radio interference. For the same reason, meticulous care has been taken to generate a pure sine-wave, as this waveform contains no harmonics, which would give rise to difficult-to-suppress, high-frequency interference signals.

The h.f. power is almost completely dissipated in the bulb

The power coupler generates a high-frequency magnetic field in the discharge vessel, directed along the axis of the coil. This field in turn induces a secondary electric field perpendicular to the magnetic field (Fig. 102). This high-frequency electric field accelerates the electrically charged particles (electrons and positive ions) present in the fill gas, thus causing collisions resulting in excitation and ionisation, and the emission of ultraviolet and visible radiation (see for further explanation Lesson 7, Section 1.3.1). Provided the inductive power coupling is realised effectively, practically all the power dissipated in the bulb will be absorbed by the discharge and converted into other forms of radiant energy, and only very little r.f. radiation from the antenna coil will stray outside the discharge bulb.

8.3.3 Ignition and run-up

A high-voltage pulse initiates the discharge

For fast and reliable starting, an ignition pulse of approximately 1300 volts and 15 milliseconds duration is sent through the antenna coil. The ignition pulse is powerful enough to also ensure reliable hot restrike of the lamp after a power interruption.

The fill gas contains a small dose of radioactive krypton$^{85}$. This isotope emits electrons in the form of $\beta$-radiation$^*$), so that sufficient free electrons are always present in the discharge bulb for reliable starting.

The ignition pulse first initiates a capacitive glow discharge near the wall of the power coupler cavity (Fig. 103), in a similar way as is produced by the external conductive strip or wire along the discharge tube that is used as a starting aid in several other lamp types (see Lesson 7, Section 3.2 and Section 4.2.2 of this lesson). The glow discharge generates sufficient free electrons by ionisation to release the main arc discharge, which is sustained by inductive power-coupling.

$^*$ This radiation will hardly penetrate through the wall of the glass bulb, and anyhow too weak to cause harm under any circumstances, see also Section 5.2.1.
The run-up process is characterised by a steady increase of the temperature inside the discharge vessel. However, if nothing were done to speed it up, the corresponding increase of the light output would be a very slow process. This is because the main amalgam is located at a remote cool spot far from the centre of the discharge, in one of the exhaust tubes at the bottom. An auxiliary amalgam is therefore employed, which is found on the wall of the cavity that houses the power coupler, a spot that most quickly gains temperature during the run-up period.

The different functions of the two amalgams

The main and auxiliary amalgam differ in their composition. The auxiliary amalgam is an indium-mercury compound with a higher melting point than the main amalgam, which consists of an eutectic system of bismuth, indium and mercury. After ignition, the auxiliary amalgam heats up very quickly and starts releasing mercury. Within about five seconds the mercury-vapour pressure built-up is sufficient for the lamp to emit 40 per cent of the nominal luminous flux, and after half a minute almost the full light output*) is reached. From this moment on, during the following run-up period, the temperature of the bulb wall determines the mercury-vapour pressure, just as in a normal fluorescent lamp.

The increasing temperature in the discharge vessel heats up the main amalgam, which slowly starts to evaporate mercury. The main amalgam has a lower melting point and therefore a higher mercury-vapour pressure for a given temperature than the auxiliary amalgam, so that, once thermal conditions have become stable, the main amalgam will control the mercury-vapour pressure in the lamp**). The complete run-up process - although hardly noticeable in terms of light output - takes well over one hour (Fig. 104).

8.4 Performance characteristics

8.4.1 Luminous efficacy

The system efficacy of QL fluorescent induction lamps is 65 - 70 lm/W. By comparison, the system efficacy of integrated compact fluorescent lamp types (SL* and PL*Electronic) varies between 40 and 65 lm/W.

*) This is the run-up behaviour under nominal operating conditions. Even in the worst case, 70 % of the nominal light output will still be reached within one minute.

**) Although the temperature of the auxiliary amalgam will still be higher than that of the main amalgam, if temperature difference is no longer sufficient for it to determine the mercury-vapour pressure.
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8.4.2 Energy balance and influence of ambient temperature

Performance is fairly constant within wide temperature limits. Fig. 105 shows the energy balance of the 85 watt QL lamp system. It appears that 17.5 per cent of the input power is converted into visible and (very little) UV radiation, the rest being ‘lost’ in the form of heat. Most of the heat is generated in the induction coil of the power coupler, where the temperature can rise to as high as 250°C. Lamp performance in terms of luminous flux and luminous efficacy, however, is principally determined by the temperature of the main amalgam, which is located in one of the exhaust tubes at the bottom of the bulb. Adequate lamp performance, that is to say a luminous flux of more than 85 % of the nominal value, is obtained if the temperature of the main amalgam is maintained within the range of 50°C to 122°C (Fig. 106). The amalgam temperature is influenced by the outside ambient temperature, the burning position, and the thermal insulator properties of the luminaire. In practice, no problems will arise provided the recommendations from the lamp manufacturer with respect to the luminaire design have been followed.

8.4.3 Stray radiation and radio interference

Despite all the preventive measures taken, QL lamps do nevertheless produce some stray radiation at radio frequencies, but then so do most discharge lamps. There is no indication that this type of radiation - even at high levels - is harmful to living beings but it can cause interference with some types of electronic equipment, notably radio and television receivers, computers and pacemakers. Therefore, the maximum permissible stray-radiation level is covered by strict international regulations.
Interference by conduction or radiation

Interference can take place in two different ways: by conducting through the mains to other equipment connected to the mains supply, and by direct radiation from the antenna coil. Conducted interference is counteracted by the presence of a low-pass filter between the mains input and the h.f. generator, which effectively prevents high-frequency signals from entering the mains.

Radiated interference is prevented by the construction of the luminaire

Interference by radiation can be in the form of stray electric and magnetic fields. Electrical interference is largely suppressed by the counter winding on the antenna coil (see Section 8.3.1), whilst the magnetic field is almost entirely destroyed by the discharge (see Section 8.3.2). The remaining, very low interference levels can be shielded off by judiciously positioned metal parts in the luminaire, such as a metal reflector, support rods, or a wire-gauze screen. Fig. 107 gives some examples. Provided the screening is properly done, the actual levels for all types of interference will be well below the maximum permissible values.

The UV-radiation level of QL lamps is not higher than that of any 80-series fluorescent lamp.

8.4.4 Lamp life and depreciation

Expected lifetime had to be computed instead of measured

The indicated life expectation of a QL lamp system is 60,000 hours, or almost seven years of continuous operation. For practical reasons, this value is not based purely upon tests carried out on a large number of lamps under rated conditions - as described in Lesson 7, Section 4.1.1 - but was initially computed on the basis of known data on the depreciation rate of the phosphors used and the statistical failure chance of the individual electronic components. The assumption that a light output depreciation of 30 % is the maximum acceptable value for economic operation resulted in a lifetime prediction of 60 000 operating hours. The corresponding expected failure rate calculated for the electrical circuitry is less than 20 %.

In the meantime, lifetime measurements on QL systems have become available, which indicate that these figures may be even better. Moreover, the QL design is such that in the case of an early failure, only the defective part needs to be replaced.
8.5 QL lamp types

At present, two QL lamp wattages are available, 55 W and 85 W (Fig. 108), both in colours 82 (2700 K), 83 (3000 K) and 84 (4000 K).
Conclusion

Of all the discharge lamp types the tubular fluorescent is by far the most popular and widely used. Its versatility in application – indoors as well as out – is reflected in a great many types and versions to suit any sphere of use. The same also applies to lamp circuitry, which over recent years has seen the ever increasing use of electronics to replace traditional components. This has lead to very promising improvements with respect to lamp performance and system efficacy.

The latest advancement is the fluorescent induction lamp, which combines the positive features of other fluorescent lamp types with a very compact, globular form. Added to this comes an unprecedented lifetime, which offers a great freedom of luminaire and lighting design and reduces maintenance to practically zero.
1. If, leaving all other parameters the same, the fluorescent coating were to be applied to the outside instead of the inside of the tube, the light output would be:
   a. slightly higher
   b. slightly lower
   c. much lower
   d. no perceptible difference

2. If, leaving all other parameters the same, the tube diameter of a fluorescent lamp were to be decreased this would result in:
   a. a higher lamp voltage
   b. a lower lamp voltage
   c. a higher starting voltage
   d. a lower starting voltage

3. An outside conductive strip is chiefly found on:
   a. d.c. lamps
   b. 26 mm lamps
   c. cold-cathode lamps
   d. rapid-start lamps

4. If the mercury capsule is left out of an otherwise complete 20W fluorescent lamp, then the lamp will:
   a. not start
   b. start, but produce hardly any light
   c. produce red light
   d. burn out after a short time

5. A rapid-start lamp can be used in a starter circuit without trouble. What will happen to a (38 mm) starter lamp in a rapid-start circuit?
   a. the lamp will not start
   b. the electrodes will burn out after a short time
   c. the lamp will only start at normal temperature conditions, and then operate without trouble
   d. the lamp will make several start attempts, but not burn stably

6. A colour 84 fluorescent lamp has a longer economic life than a similar colour 33 type, because:
   a. it is more expensive to replace
   b. it has a longer average life
   c. it shows fewer starting problems with age
   d. it has a lower depreciation rate

7. The published luminous efficacy of a 9 W PL-S lamp is 68 lm/W whereas that of a clear-glass 9 W SL* lamp is 50 lm/W. The difference is chiefly caused by:
   a. the use of amalgam in SL* lamps
   b. the difference between lamp and system efficacy
   c. transmission losses in the outer envelope
   d. the use of more efficient phosphors in PL lamps, made possible thanks to a lower tube wall temperature

8. In a green fluorescent lamp the same green phosphor is used as in three-band lamps of the 80-series. How will the luminous efficacy of a green lamp compare with that of an 80-series lamp of the same wattage?
   a. it will be higher
   b. it will be lower
   c. it will be practically the same
   d. they cannot be compared, because of the difference in colour appearance

9. Which of the following electrical characteristics of the lamp circuit does not result in an improved system efficacy?
   a. square waveform
   b. high frequency
   c. high power factor
   d. low ballast losses

10. The free electrons in the discharge vessel of a QL induction lamp are accelerated by:
    a. krypton
    b. collision with mercury atoms
    c. the magnetic field
    d. the secondary electric field