Equipment Energy Efficiency

Training Guide: The Basics of Efficient Lighting

A Reference Manual for Training in Efficient Lighting Principles

Second Edition, June 2019

A joint initiative of Australian, State and Territory
and New Zealand Governments.

This document is available at [the Energy Rating website.]()

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Contents

Please note, this version of *The Basics of Efficient Lighting* training manual does not include the appendices.

To download the appendices, please go to: http://www.energyrating.gov.au/document/training-guide-basics-efficient-lighting

Introduction

The purpose of this training material is three-fold. The first aim is to provide the lighting and allied industry workforce with an overview of the key principles of light and lighting which includes an understanding of basic design concepts and lighting technologies currently available, in the context of sustainability. The second aim is to help users understand the importance of energy efficiency and the implications of choosing a product in the overall scope of energy consumption. It also aims to assist users with the selection process when specifying, recommending, designing and installing various lighting systems.

The first edition of this manual was published in 2010. Since this time LED lighting and other changes have been occurring in lighting, at a rapid pace. To reflect these changes, this second edition was published in 2018.

In residential dwellings, lighting energy consumption increased dramatically with the popularity of halogen downlight systems, which are grossly inefficient when compared to the increasing range of residential LEDs that are now available. Similar changes are underway in almost all lighting market sectors, including a transition from linear fluorescent to LED. In both of these cases, improved lighting technical and design knowledge may lead to higher quality and more efficient installations.

Qualification as a lighting designer requires a great depth of knowledge in the lighting design process. This knowledge is acquired through extensive, detailed training, covering a large variety of lighting design applications such as interior lighting, (differentiated into commercial, retail, industrial and residential), floodlighting, emergency and exit lighting, exterior lighting, road lighting, public lighting, facade lighting, and theatre lighting. Detailed design methodology is beyond the scope of this document.

This chapter of the manual introduces the basic concepts of light and lighting, and explores the key requirements of a lighting system and what standards need to be met. It also explains what we mean by sustainability and energy efficiency and how good lighting design can contribute to these.

1.1 The function of lighting

We need light to see the world around us. Light is a natural phenomenon vital to our very existence. The advent of a wide range of electric light sources means we are now less dependent upon light from the sun, moon and stars and flames from combustible fuels. The quality, quantity and intensity of light around us greatly affects our visual appreciation of our surroundings. It is important for us to understand the relationship between light, colour, what we see and how we see it.

Artificial lighting would not be required if our buildings were not occupied or visited by human beings. The sole purpose of lighting installations is to allow people to adequately perform physical or visual tasks, and the effectiveness of performing these tasks correlates to the quantity and the quality of the lit environment.

In the ***ideal world*** lighting installations should be designed primarily for the comfort of the occupants within. The task efficiency, energy efficiency and aesthetic value of the lighting installation a secondary consideration. However, the importance of energy efficiency is greatly increased with issues such as climate change and energy pricing, which all impact in our community.

The major aim of lighting is to provide the correct lighting solution for the installation to attain the highest quality product, or image, whilst realising the need for energy efficiency. The quality of a commercial lighting system is paramount - the quality of work output, morale of employees and perceived working conditions are all directly related to the lighting system installed.

The most important thing to remember is that lighting is based on ***50% fact*** and ***50% psychology***. The needs of the site and the occupants, or potential customers, are critical, and many complaints stem from the perceived inadequacies of the lighting system.

1.2 Why we use lighting

Artificial lighting is a key part of our everyday lives. We use it to:

- Help us find our way around, to assist visibility
- Provide a safer environment
- Increase the number of useful hours in the day
- Help perform visual tasks, increase productivity
- Display objects and / or control how they appear, improve sales
- Attract attention
- Improve employee working conditions

It is also possible to use lighting to reduce fatigue, encourage concentration or to improve awareness or decision-making. It can create an atmosphere of comfort, relaxation or trust or help people recover from illness or fatigue.

1.3 Fitness for purpose

It is important that any lighting system is fit for purpose: It should provide a quality and quantity of light that is appropriate for the environment in which it is being used; enable tasks to be performed efficiently and effectively; be perceived as comfortable and give people a high level of satisfaction. The aim is to achieve this whilst providing a good balance of cost and energy consumption through good design and optimum selection of products.

1.4 Definition of energy efficiency

Energy efficiency is defined as optimisation of energy consumption, with no sacrifice in lighting quality. It is a combination of thoughtful design and selection of appropriate light source, luminaire and control system selection, made in conjunction with informed choices of the illumination level required, integration and awareness of the environment or space which is being lit.

It is very easy to produce an inefficient lighting installation using efficient equipment.

Historically, the most common cause of an inefficient lighting system in the home was the excessive use of low voltage tungsten halogen downlights to produce extremely high lighting levels in some sections of the house (for example the breakfast bar in the kitchen). By producing a high lighting level in the kitchen (in excess of 1000 lux), the rest of the house can look dull by comparison. Typically we try to increase the lighting levels in the rest of the house to match the kitchen, rather than reducing the lighting levels in the kitchen in the first place. This scenario is also prevalent in offices, industry and particularly in retail applications.

1.5 Definition of lighting design

Lighting design is often incorrectly considered to be simply the selection of the lighting equipment for a system. While selecting the most cost-effective and energy-efficient products is important, they are just the tools to achieve the design. True lighting design involves assessing and meeting the needs of the people who use the space and balancing function and the aesthetic impact supplied by the lighting system.

Lighting is an art as well as a science. This implies that there are no hard and fast rules for lighting design nor will there be one ideal or optimum solution to a lighting problem. More often than not, the lighting designer is confronted with a set of conflicting requirements for which priorities must be allocated before a satisfactory compromise can be found. There is no substitute for experience, careful planning, assessment and analysis.

This document allows the reader to be suitably informed of the basic lighting concepts to enable them to progress with a lighting design course which is delivered under a separate program, and covers a number of regulated design requirements.

1.6 Sustainability and the importance of energy efficiency

There are many definitions of sustainability yet probably the most straightforward is that in the Brundtland Report, '*Our Common Future'*. This states that 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.'

It is about sensibly and effectively using the resources currently available. Energy is one such resource and energy efficiency is a key component of sustainability. Linked to this are the environmental benefits associated with using less energy, primarily a reduction in the production of greenhouse gases which are a major contributor towards climate change.

Lighting accounts for between 5 and 15% of residential energy use and up to 40% of commercial building energy use, and continues to increase. In certain business types, for example the retail sector, lighting can account for up to 80% of energy use. This is due to long operating hours and the need to "keep things bright" and stand out from the competition.

Therefore, in this context, greater sustainability can be achieved by making a conscious decision to reduce the amount of electricity used through appropriate lighting design (including the use of natural light and design techniques to reduce the amount of artificial lighting needed) and by selecting energy efficient luminaires and effective control systems. The manufacturing process and the choice of materials to make luminaires also have a relatively small impact on sustainability in comparison to operational energy consumption.

2 Fundamentals of Light and Photometry

This section describes the nature of light, how it is perceived by the eye and how it is measured.

2.1 The Nature of Light

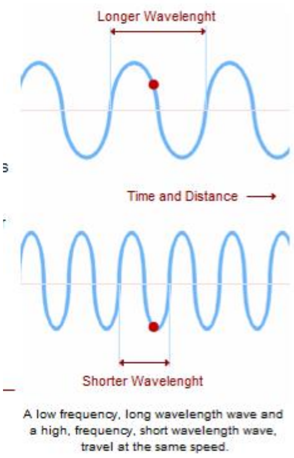
Light is one of the forms of energy known as electromagnetic radiation, which also includes heat, radio waves and X-rays. Electromagnetic radiation travels outwards from its source in a waveform, like ripples in a pond. Electromagnetic waves travel in space at approximately 300,000 kilometres per second. This is commonly known as the speed of light, but it is the same for all electromagnetic waves.

2.1.1 Velocity, frequency and wavelength

The rate at which an electromagnetic wave 'vibrates' is known as the frequency (measured in Hertz (Hz)). Different frequency electromagnetic waves are responsible for different effects, such as light, heat, radio waves and X-rays.

The wavelength is the distance the wave travels in one complete cycle.

Because the velocity (speed) of electromagnetic radiation in air is always constant (at approximately 300,000 kilometres per second), the wavelength decreases as the frequency increases and vice-versa as shown in the diagram.



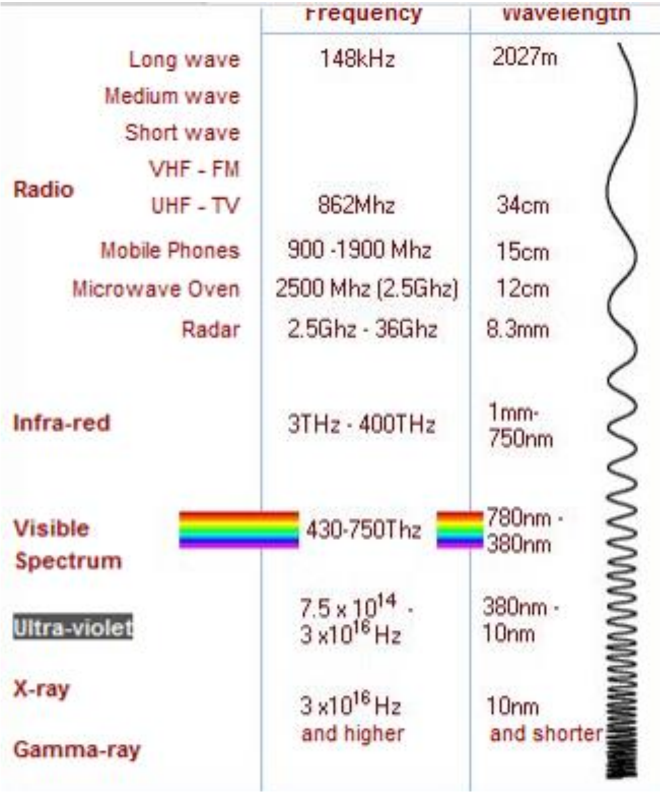
From this fact, the following relationships can be derived:

- Velocity = frequency x wavelength, and hence:
- Frequency = velocity/wavelength, and
- Wavelength = velocity/frequency

2.1.2 The electromagnetic radiation spectrum

The table below shows how electromagnetic waves of varying frequencies, produce different effects such as radio, light, and X-rays.

The small coloured bands show the range that represents visible light. This visible colour spectrum (more commonly shortened to visible spectrum) is a very small part of the total electromagnetic spectrum.



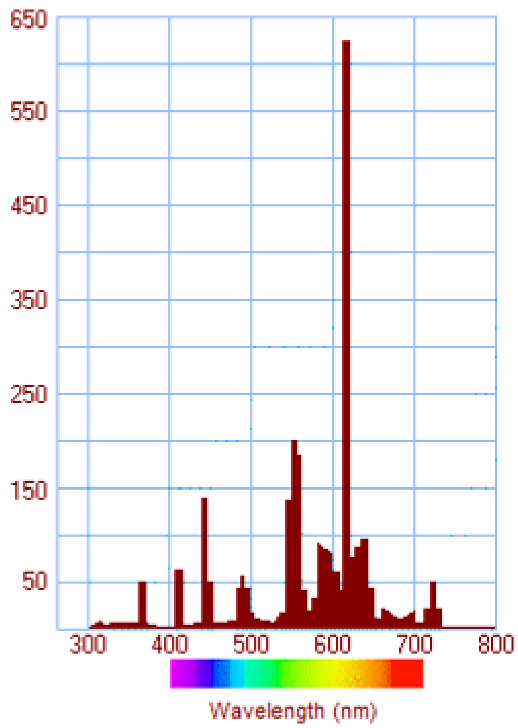
kHz=1,000Hz
MHz=1,000,000Hz
GHz=1,000,000,000Hz
THz=1,000,000,000,000Hz

nm=nanometre = 1000,000,000th of a metre

2.1.3 The visible spectrum

The visible spectrum extends from a wavelength of approximately 360 nanometres to 780 nanometres.

One way to specify the performance of a lamp is to show how its light is made up of the individual colours across the visible spectrum. This is done with a spectral power distribution graph (y axis = Power (mW/5nm/1,000lm):



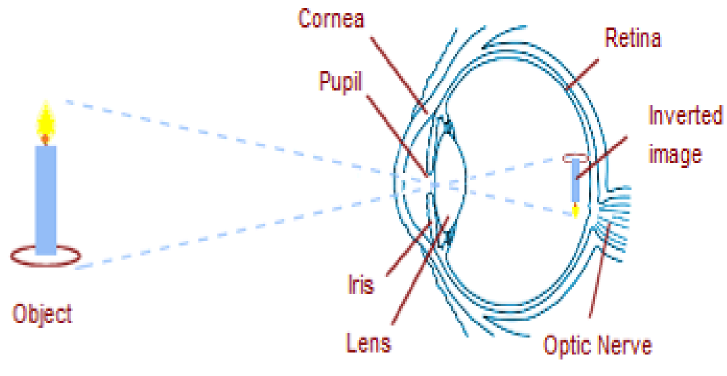
Spectral Power Distribution Graph (the main power output of this lamp is at 620nm)

2.1.4 The eye and vision

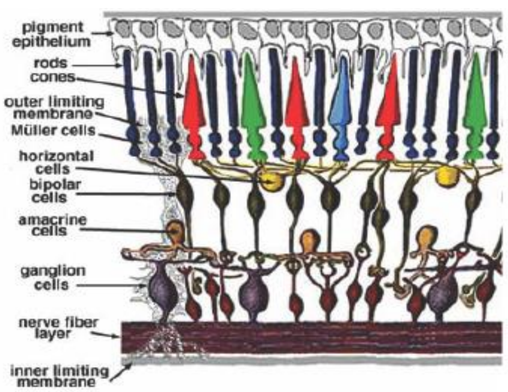
We need light to see. When light reaches an object, some is absorbed and some is reflected by the object. Some of the reflected light reaches the eye and enables it to be seen.

As shown in the diagram, light from the object passes through the pupil and is focused by the lens onto the light sensitive retina. The lens is attached to a set of muscles which contract and relax to change the shape of the lens. It is this change in shape that allows both near and distant objects to be focused. The retina converts light into electrical impulses that are sent to the brain by the optic nerve. It is made up of two kinds of light sensitive cells, rods and cones. The cones distinguish colour information, but need a high level of light to work well. Rods distinguish only black and white, but work well at low light levels which explains why colour vision does not work well at night.

As can be seen, the image on the retina is inverted, but this is corrected during processing in the visual cortex of the brain.



A simplified cut-away view of the human eye



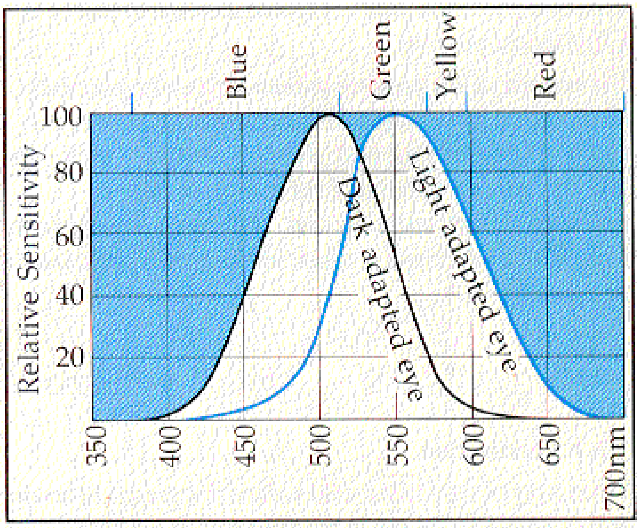
2.1.5 The sensitivity of the eye

The sensitivity of the eye is not even over the visible spectrum, but varies with the wavelength. The cones operate during the day and normal daylight conditions and enable us to see in detailed colour. This is known as PHOTOPIC or daytime adaption. As the light level drops, say to that of a well-lit street, the cones become less effective and are assisted by the more sensitive rods. Therefore, the eye is using a mixture of cones and rods to see.

However, as the rods can only "see" a black and white image, the overall impression is much less brightly coloured. This is called MESOPIC vision. At even lower levels, much lower than average street lighting or moonlight, the cones cease to function. The eye loses all its facility to see in colour and the rods take over, giving completely black and white vision, called SCOTOPIC, or night-time adaption.

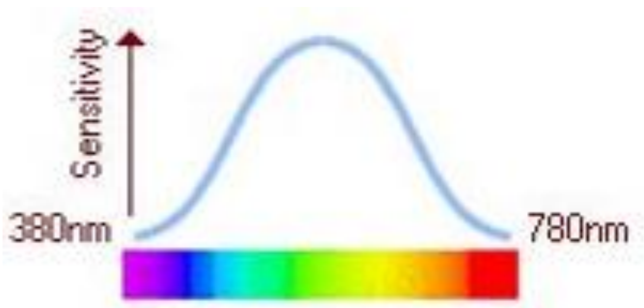
These different adaptions are important because not only does the eye discriminate between different wavelengths of light with the sensation of colour, it is also more sensitive to some wavelengths than others - and this sensitivity alters between photopic and scotopic vision.

For photopic vision, the eye has peak sensitivity at 555 nanometres, which is a yellow-green colour. However, for scotopic vision, peak sensitivity moves to 505 nanometres which is blue-green light, although the vision is in terms of black and white. The mesopic vision peak will be somewhere between the two. This accounts for the perception that white light appears brighter at night than yellow light.



Relative Spectral Sensitivity of the Eye

As we get older our ability to adjust the lens' focus, reduces, and our retinas become less sensitive. The result is that we need more light and often spectacles to be able to see well.



Eye sensitivity - peak approx 550nm

2.2 Introduction to Photometry

Light sources emit electromagnetic waves in the Ultra Violet (UV), visible and infra-red spectrum. Measurement of all these is called radiometry. Photometry is a special branch of radiometry in which we only measure visible light.

Four terms are used to describe light:

- Luminous Intensity (candela)
- Luminous Flux (lumen)
- Illuminance (lux)
- Luminance (candela/m^2)

In addition, the term efficacy is useful when describing lamps, and is a measure of how efficiently they convert electricity to visible light. Efficacy is measured in lumens per watt.

When we refer to energy efficiency within lighting systems, we use the system efficacy which includes the losses of any control system incorporated in operating the lamp.

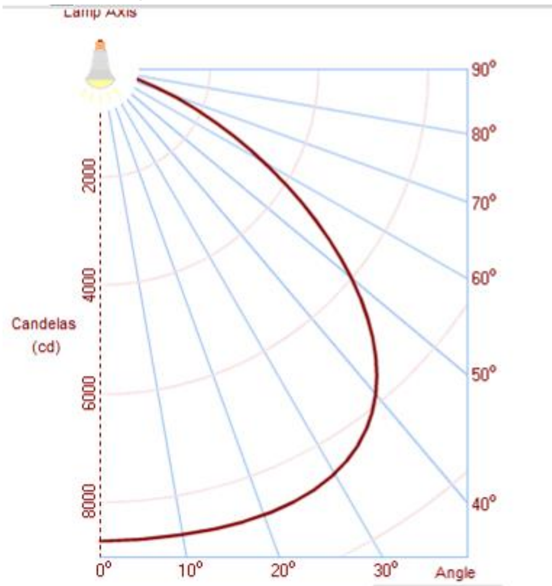
As an example, the system efficacy of a 1 x 28 watt T5 fluorescent lamp (tri-phosphor with 2600 lumen output at 25°C) operating on a standard electronic ballast of 3 watts loss would be:

28 watt + 3 watt = 31 watts divided by 2600 lumens = 83.87 lumens/watt

2.2.1 Luminous Intensity

The luminous intensity is a measure of how much flux (lumens) is emitted within a small conical angle in a particular direction from a light source (lamp) or luminaire. Its unit of measurement is the Candela. The symbol for candela is symbol is I. The intensity of light sources used to be referred to as candle power.

If a source emits the same luminous flux in all directions, then the luminous intensity is the same in all directions. For most sources, however, the flux emitted in each direction is not the same. For example the luminous intensity of a spotlight varies with angle. Similarly, the flux emitted from a luminaire (light fitting) also varies with angle. If these candela values are plotted in graphical form, then a polar distribution diagram can be produced for a luminaire or reflector lamp, as shown below.



Most reflector lamps will have a light output stated in candela. This value is the peak intensity, usually quoted at 0 degrees or directly below the lamp in the vertical position as shown above.

2.2.2 Total Luminous Flux

Candelas indicate how bright a light is in a given direction. The term luminous flux is used to measure the visible light output of lamps, where light is not directional. It refers to the visible light emitted in all directions at any given moment (whereas radiant flux is the total radiation (ultraviolet, visible and infrared) being emitted from a light in all directions). The symbol for luminous flux is F or Φ (phi).

2.2.2.1 Lumens

It is impractical to use the watt as a measure of light because of the variation in sensitivity of the eye with wavelength. Instead we use the LUMEN which is a measurement of the rate of flow of the luminous energy, or the LUMINOUS FLUX as it is more often called. One lumen of luminous flux at 555 nanometres corresponds to a radiated power of 1/680th of a watt, but at 400 nanometres, 3.5 watts of radiated power is equal to one lumen.

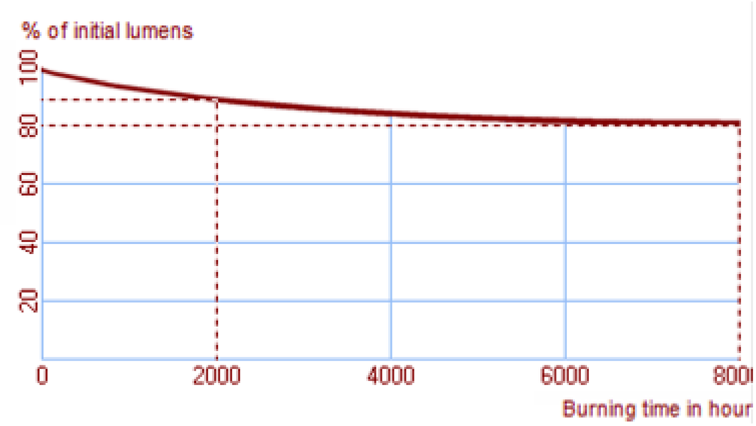
This relationship between the watt and the lumen is important as it is possible to calculate the luminous flux a particular lamp will produce by considering the radiated power at each wavelength and the corresponding eye sensitivity (as defined by the CIE) at that wavelength. This can be done mathematically or by means of specially corrected photocells with a response identical to that of the CIE standard observer.

For example, a low pressure sodium lamp emits practically all its light at wavelengths 589 and 589.6 nanometres. As this is very close to the peak photopic sensitivity of the eye, it is very efficient in terms of the number of lumens produced for each watt of power. Therefore if is possible to make a lamp which will produce 160 lumens for each watt of power. However being mono-chromatic light, the results are often undesirable.

The lumen (lm) is equal to the flux emitted by a uniform point source of 1 candela in a solid angle of 1 steradian. A steradian is the standard unit solid angle in three dimensions. As an example, the total luminous flux of a 60W GLS lamp is 710 lm. These 710 lumens are emitted in every direction from the lamp.

2.2.2.2 Lumen Maintenance

When a lamp is new its light output is at a maximum. As it burns through its life, the output declines. The term used to describe how the light output declines is lumen maintenance. It is usually shown in graphical form.



Lumen maintenance information is important for those who are responsible for maintaining or designing the lighting levels in buildings etc. It makes it possible to schedule replacement of lamps before the light level becomes too low. This is referred to as planned maintenance and often includes the cleaning of luminaire reflectors and diffusers. The lumen depreciation over the lifetime of discharge lamps (fluorescent and HID) and LEDs can be much greater than that of incandescent or tungsten lamps (noting that discharge and LED lamps typically have much longer lifetimes).

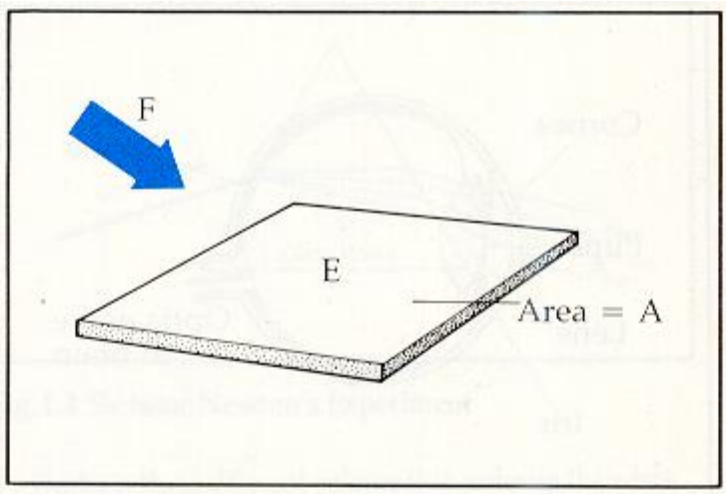
For LEDs, attention should be paid to lumen maintenance claims. LEDs can exhibit very long lifetimes, and the dominant failure modes for LEDs is typically lumen maintenance - in other words the LED simply loses light output gradually rather than simply failing.

Lumen maintenance, particularly for LEDs, is often expressed in term of an L_x value, which represents the expired time by which the light source has reached x% of its initial light output. For example, an L_{70} of 10,000 hours means that the light source should reach 70% of its initial light output by the time it has run for 10,000 hours. Note however that such claims are typically produced using “extrapolated” estimation techniques based on exaggerated testing over a shorter time period.

2.2.3 Illuminance

When a ray of light hits a solid surface, the process is known as ILLUMINATION. In the same way we have lumens to measure luminous flux, we need a measurement for the quantity of illumination or ILLUMINANCE. The illuminance E at a point on a surface is defined as the luminous flux F (lumens) incident upon a small element of the surface divided by the area A (m^2) of the element.

$$\mathbf{E = F / A}$$



Illumination and Illuminance

In the SI or International System of units, the basic unit of illuminance is the Lumen per square metre or LUX, For example, if an area of 0.1 square metres in size receives a luminous flux of 20 lumens, the illuminance which is usually given the symbol E, will equal 20 divided by 0.1, that is 200 lux,

Although the lux is the metric measurement, sometimes the imperial measurement of lumens per square foot is referred to which is also called the FOOTCANDLE in the USA. One of these imperial units is equal to 10,761ux by virtue of 10.76 square feet being equal to one square metre.

Some typical examples of illuminance levels are shown below.

Situation	Illuminance level
Very bright summer's day	100,000 lux
Overcast summer's day	30,000 - 40,000 lux
Shady room in natural light	100 - 150 lux

Light levels for working	Illumination levels
General office task	320 lux
Rough tasks with large detail	160 lux
Ordinary tasks with average detail	320 lux
Difficult tasks with fine detail	600 lux
Minute tasks, detailed inspection	1600 lux

In practice, when designing lighting schemes and predicting illumination levels it is necessary to have information not just about the lamps, but also the luminaire in which the lamp will be used. A technical specification sheet of the luminaire, showing the polar distribution diagram of the luminaire using a specific lamp, is essential to determine the light distribution and performance levels of the luminaire.

Legislation varies from country to country, but in Australia, such statutory instruments as the Building Code of Australia and Occupational Health and Safety Act require that the lighting at places of work shall be both sufficient and suitable. Sufficiency is normally taken to imply an adequate quantity of light (illuminance) both on work tasks and in areas where people circulate. Legislation is normally concerned with what is adequate, unlike the recommendations in lighting guides which focus on good practice.

Definition - Maintained Illuminance: *The defined level below which the average illuminance on any surface is not allowed to fall. It is the minimum illuminance at which maintenance operations, (such as replacing lamps and cleaning the luminaires, windows, roof lights and room surfaces), are to be carried out.*

The schedule in the Australian Standards recommends maintained illuminance for interiors according to the tasks involved. The relevant area may be the whole of the interior or just that occupied by the tasks and their immediate surround. In the latter case, the maintained illuminance of the general surround areas of a working environment should be based upon tasks that are carried out in these areas, but should not be less than one-third of the highest task illuminance, or problems of adaptation will arise.

Illuminance should be increased or decreased if task details are unusually difficult or easy to see or if the task is done for an unusually long or short time. Illuminance should be increased if there are concerns that errors could have unusually serious consequences. Where eye protection is worn, or tasks must be carried out through transparent screens, the contrast of the task may well be reduced and, in such circumstances, the illuminance on the task should be increased in an attempt to compensate. Also, if the most onerous visual tasks are to be carried out by occupants with poor sight or an average age that is higher than normal (say over 50 years), then the designer is justified in increasing the illuminance. The maintained illuminance should not be less than 500 lux for situations involving critical colour matching.

The illuminance recommendations apply to the tasks themselves, which may be complex in both shape and position. This can cause major difficulties in both prediction and measurement. It is commonly assumed that the illuminance on the task will be the same as the illuminance on a plane at the same angle and position as the task. This is good enough for most practical purposes, but is nevertheless an assumption and its validity should always be questioned.

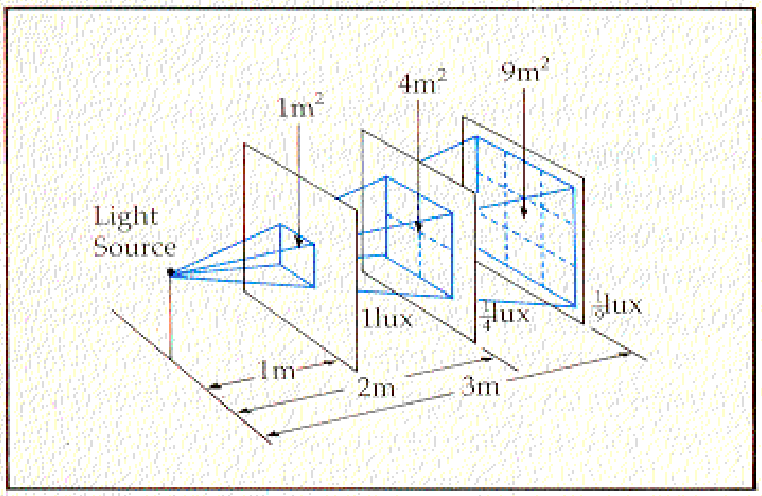
It frequently happens that the precise location of a task is not known, and therefore a horizontal plane at workstation height is usually taken. Where vertical tasks are involved, but their orientation is not known, then mean vertical (i.e. cylindrical) illuminance may be used. In addition to providing sufficient light for tasks to be carried out, the occupants must also feel that there is enough light.

When it comes to energy efficiency, the most common mistake made in designing an installation, is the installation of a lighting system that provides ***too much*** light, i.e. illuminance levels well above those recommended by the Australian Standards.

2.2.3.1 Inverse square law

Importance is placed on the illuminance required for different purposes; therefore it is essential to have a secondary method for calculating this quantity. In the mid-18th century, J. H. Lambert established one of the earliest lighting laws thus enabling the calculation of illuminance, called the INVERSE SQUARE LAW.

To understand this law, consider a cone-shaped beam of light coming from a small point source and hitting a surface some distance away. Suppose that the luminous flux within the cone is one lumen, and it strikes a surface 1 metre away, producing an illuminated area of 1 square metre. By dividing the luminous flux by the area, we can find the illuminance, which will be 1 lux.



Inverse Square Law

If the surface is moved further away to a distance of 2 metres, then the luminous flux within the cone will stay the same, but the illuminated area will increase in size to 4 square metres. This will result in an illuminance of ¼ lux. By doing this, the area has increased in proportion to the square of the distance from the light source, and the illuminance has changed inversely with the square of the distance.

If the surface is moved still further away to a distance of 3 metres, the inverse square law operates again. The area has increased in proportion to the distance squared and is now 9 square metres and the resultant illuminance falls inversely to 1/9th lux. All of this is encompassed by the inverse square law which states that; the illuminance E equals I, the intensity of the light source, divided by the distance squared.

$$\mathbf{E = I / d^2}$$

So far these calculations of illuminance have only covered situations where the rays of light hit the surface at right angles. Here the illuminance**,** which is the flux falling onto the surface divided by the area, can be found by using the inverse square law.

2.2.3.2 Cosine Law

If the surface is turned so that the rays hit it at an angle, the illuminated area will increase in size and the illuminance will drop accordingly. The ratio of the original illuminated area to the new area is equal to the cosine of the angle through which the surface has been moved. Therefore the illuminance will fall by the factor of the cosine of the angle.

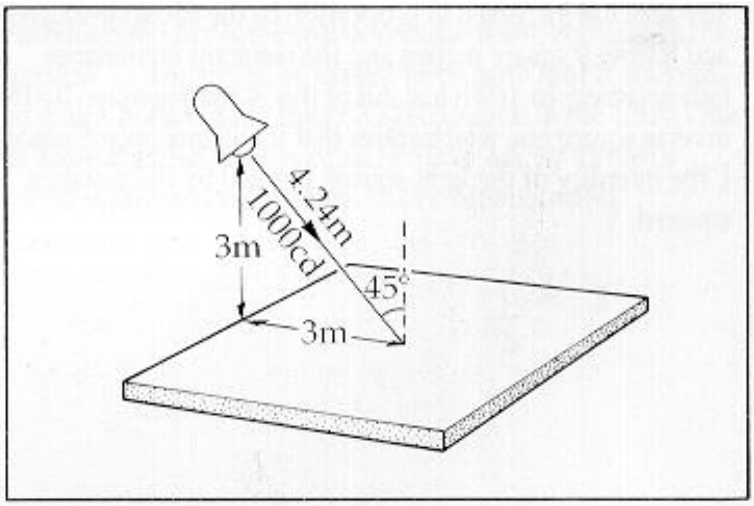
This is where Lambert's second law comes in; the COSINE LAW of illuminance. If a surface is illuminated to 100 lux and is twisted through an angle of 60 degrees, then the illuminance will fall to half or 50 lux because the cosine of 60 degrees is 0.5. This cosine law can be combined into one equation with the inverse square law:

Returning to the angled spotlight mentioned earlier, if it is 3 metres above the floor, aiming at a point 3 metres away, and its intensity in this direction is 1000 candelas, the distance from the point of illumination to the spotlight is calculated using Pythagoras theorem, and is 4.24 metres. The light is striking the floor at an angle of 45 degrees so using the combined inverse square and cosine law equation, we can calculate the illuminance.

$$\mathbf{E = I / d^2 \ Cos\ A}$$
$$\mathbf{= 1000 / 4.24^2 \ Cos\ 45}$$
$$\mathbf{= 39\ lux}$$

These calculations have only referred to one light source. But when there are several, the illuminance is calculated in the same way for each source in turn, and then these are added together for the total illuminance.

This is the basis for computer aided lighting design software which calculates the illuminance contribution from all luminaires in a room and adds them together through a series of point by point calculations and inter-reflectance assumptions.



Inverse Square Law and Cosine Law – Example

High pressure discharge light sources normally conform to the inverse square law when calculating illuminance, but fluorescent fixtures are larger and need to be dealt with separately.

For most practical applications, the inverse square law can be used with reasonable precision if the point of illuminance is more than five times away in distance than the maximum dimension of the light source. In the case of a 600 millimetre (2ft) fluorescent tube, the inverse square law is sufficiently accurate at distances of 3 metres or more.

2.2.4 Luminance

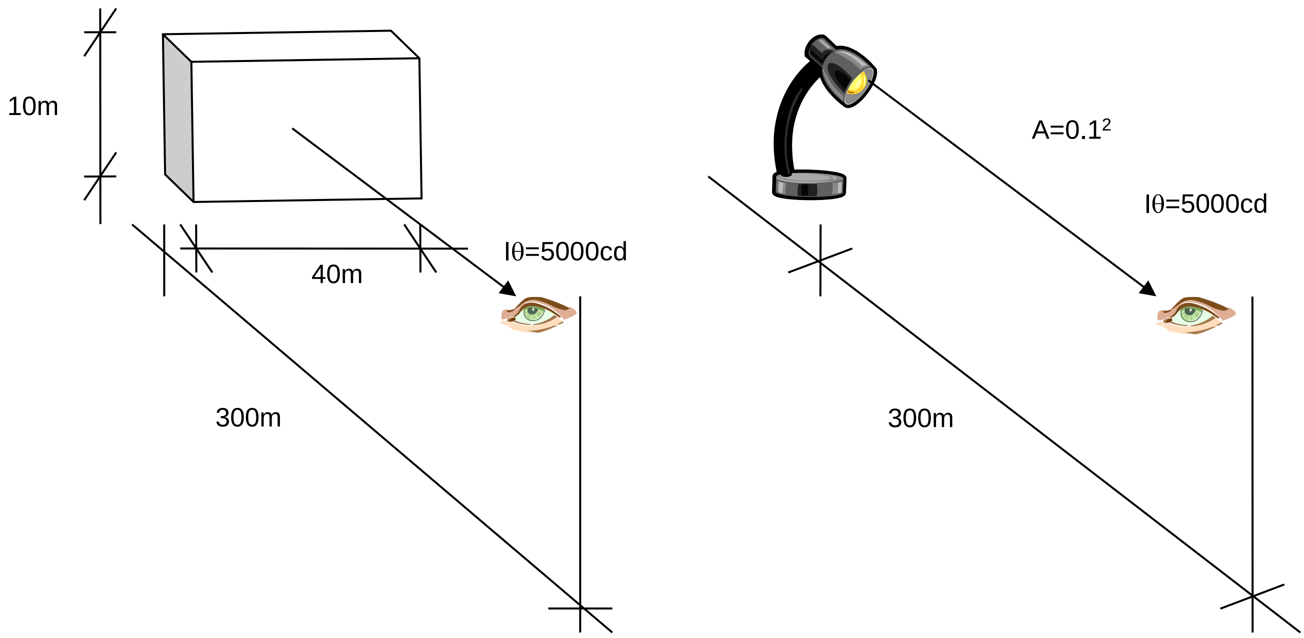
Luminance is the measure of the amount of light emitted from a surface. This surface can be as small as a pixel (or LED surface) or as large as a wall or even the sun. It is measured as luminous intensity (candela) per unit area of light emitting surface.

This is usually candelas per square metre (cd/m^2) and the symbol is L (sometimes B). Whereas brightness is qualitative (it depends on our eye adaption at the time), luminance is an absolute value. Some examples of luminance for common light sources are shown below.

Light source	**Luminance**
Solar disk at noon	1,600,000,000 cd/m^2
Solar disk at horizon	600,000 cd/m^2
Frosted bulb 60W	120,000 cd/m^2
T5 cool white fluorescent High Output	26,726 cd/m^2
T5 cool white fluorescent High Efficiency	17,400 cd/m^2
T8 cool white fluorescent (triphosphor)	11,000 cd/m^2
Average clear sky	8,000 cd/m^2
Moon surface	2,500 cd/m^2
Average cloudy sky	2,000 cd/m^2

In simple terms, the luminance is the product of the illuminance arriving on the surface and the reflectance of the surface. The eye sees luminance rather than illuminance. Therefore with the same illumination, by changing the surface reflectance, the luminance of the surface can change proportionally.

As an example, if we have one large object, an internally illuminated sign - 40m x 10m and a small object such as a small floodlight. The intensity in a direction at right angles = 5000 candela in both cases.



$$E = \frac{I}{d^2} = \frac{5000}{300^2} = 0.06 lux$$

The small floodlight has an area = 0.1 m^2 with the same intensity of 5000 cd. Both objects are viewed from 300 m.

The illuminance produced on the eyes of the viewer will be the same for both objects (Inverse Square Law).

But this does not take into account the fact that the internally illuminated sign looks larger and less bright than the small floodlight.

However, the Luminance L will be –

Building
$$L = \frac{I}{A} = \frac{5000}{40x10} = 12.5\ cd/m^2$$

Floodlight
$$L = \frac{I}{A} = \frac{5000}{0.1} = 50000 cd/m^2$$

*Luminance is a measure of the concentration or Intensity Density of a light source.

2.2.5 Efficacy

The word 'efficacy' is now an established lighting term, used to describe how efficiently a lamp or light source converts electrical energy into visible light. Its unit of measurement is lumens per Watt, usually written as lm/W. For example, the total luminous flux of a tungsten incandescent 60W GLS lamp (no longer able to the sold in Australia) is around 710 lm. Therefore the efficacy is 710 / 60 = approximately 12 lm/W.

The efficacy of any light should include the power losses of the control gear. So a 36 watt T8 fluorescent lamp produces around 3450 lumens, and a typical ferro-magnetic ballast has a loss of around 8 Watts. Therefore the efficacy is 3450 / (36 +8) = 78 lm/W.

Some of the light from the lamp output will also be absorbed inside the luminaire. If the luminaire has a “light output ratio” (LOR) of 50%, then half of the lamps’ light is absorbed inside the luminaire. Thus the net efficacy falls to 39 lm/W. LOR calculations are less applicable to LED “integrated” luminaires which embody the LED light source and all associated componentry within one integrated unit.

A chart showing the efficacy of most lamps is shown in the Lamp choice section of this reference document.

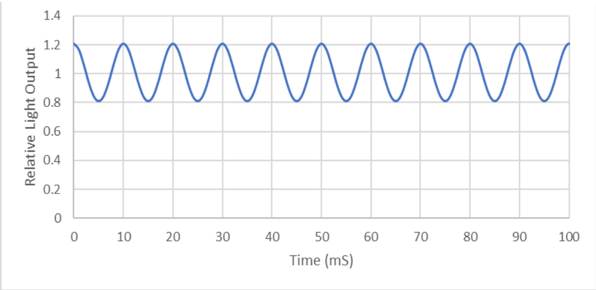
2.2.6 Temporal Light Modulation

Temporal variation in light output from a light source is defined by CIE as temporal light modulation, TLM. (This is the more formal term for “flicker”.) The different perceptions by people of TLM are collectively defined by CIE as temporal light artefacts, TLA.

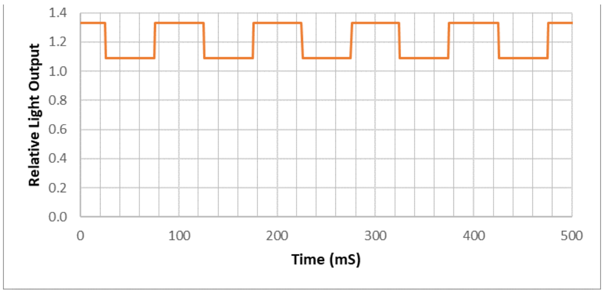
Temporal light modulation can be random due to extraneous causes or it can be periodic (cyclical). Under certain circumstances periodic variations (known as frequency with the units of Hertz[1]) can have an adverse impact on people’s health (discussed in Section 7.2).

Periodic variations in light output are manifested through two basic phenomena. The simplest is where the level of light output follows the underlying primary oscillation of the power supplied to the light source. Some examples of these waveforms are illustrated in Figure 1: sinusoidal, rectangular and triangular.

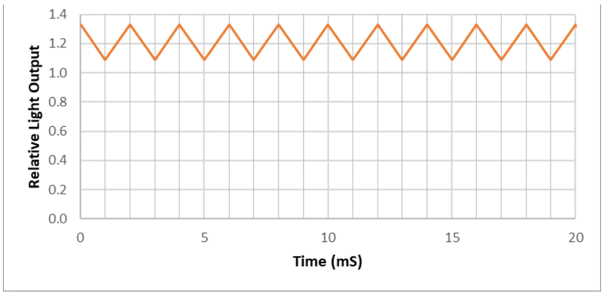
[1] The International Standard unit for frequency is Hertz (symbol: Hz). It is defined as the number of cycles occurring per second for a periodic waveform. For example, a light source varying in output at a frequency of 100Hz means the light cycles from a maximum through a minimum and back to a maximum light output 100 times per second.



(a) Sinusoidal waveform



(b) Rectangular waveform



(c) Triangular waveform

Figure 1: Periodic waveforms

The second phenomenon, Figure 2, is where the amplitude of the primary oscillation frequency has a periodic (lower frequency) variation as well.

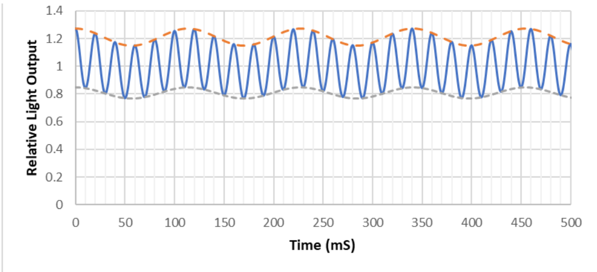


Figure 2: Sinusoidal waveform with a periodic modulation of the amplitude

For both phenomena, the variation in light level (modulation) can be quantified by the metric, percent flicker, which is the percentage modulation for the frequency of that particular light variation waveform. As illustrated in Figure 3, the percent flicker is defined as:

$$\%\,Flicker = \frac{(E_{Max} - E_{Min})}{(E_{Max} + E_{Min})}$$

Where, E is the light measurement. (In theoretical terminology, this is the ratio of the amplitude of that specific frequency component to the constant DC component).

In some cases, there may be more than one periodic light variation occurring at different frequencies. In relation to these more complex waveforms, the measured percent flicker generally relates to either the lowest or the dominant frequency component, as this is where human perception of the flicker will have highest probability. The lowest frequency may be due to the frequency of any amplitude modulation of the primary waveform (see Figure 3).

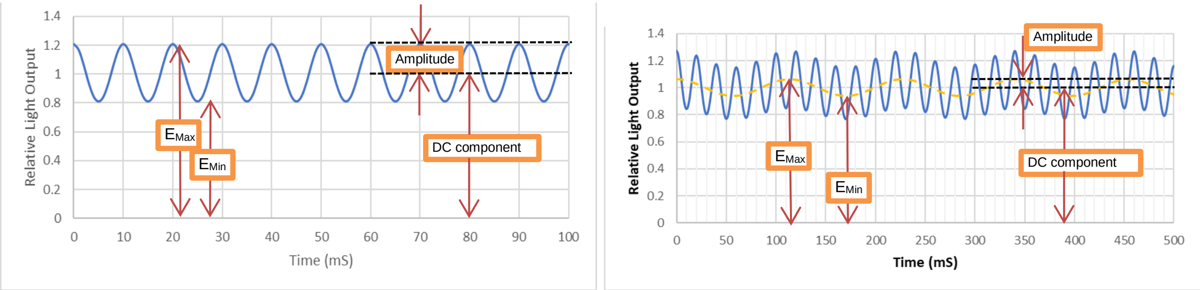


Figure 3: Illustration of measurements for % flicker metric for the primary waveform (left) and the amplitude modulating waveform (right)

Temporal variation in light output from a light source can have visual and non-visual effects on a person. The term for these effects is defined by the International Commission on Illumination (CIE) as **Temporal Light Artefacts** (TLA).

There are three situations defined by the CIE where TLAs are visually perceivable.

2.2.6.1 Flicker

Flicker occurs where the:

- light source is stationary, but the light output varies in intensity or spectral composition (i.e. colour)
- observer's eyes are not moving (i.e. without saccades: without large eye movement)
- illuminated object is stationary
- variation in light is above the threshold of visual perception
- and in the approximate frequency range from 0.5 Hz to 35 Hz.

The recommended metric for flicker is Short-term flicker severity (light measurement), P_{st}^{LM}. A value of 1 means a person of normal vision will perceive flicker 50% of the time that it is present. The higher the value the higher the probability of perceiving the effect.

2.2.6.2 Stroboscopic Effect

Stroboscope visibility effect occurs where the:

- light source is stationary, but the light output varies in intensity or spectral composition (i.e. colour)
- observer's eyes are not moving (i.e. without saccades: without large eye movement)
- illuminated object is moving (translation or rotation)
- variation in light is above the threshold of visual perception
- and in the approximate frequency range from 90 Hz to 2,000 Hz

The Stroboscope visibility effect gives the impression that the object is moving at a different rate to its actual translation or rotation speed.

The recommended metric for stroboscopic visibility effect is stroboscopic visibility effect measure, SVM. A value of 1 means a person of normal vision will perceive a stroboscopic effect 50% of the time that it is present. The higher the value the higher the probability of perceiving the effect.

2.2.6.3 Phantom Array Effect (or Ghosting)

Phantom array effect occurs where:

- the light source is stationary, but the light output varies in intensity or spectral composition (i.e. colour)
- the observer's eyes are moving (e.g. large eye movement known as saccades)
- the illuminated object is stationary
- the variation in light is above the threshold of visual perception
- and in the approximate frequency range from 120 Hz to 2,500 Hz

The Phantom array effect gives the impression of a ghosting trail of the object in a person's vision.

There is currently no recommended metric for phantom array effect.

2.2.6.4 Temporal Light Modulation and lamp technology

As part of their normal operation, fluorescent lamps, both linear and compact fluorescent lamps (CFLs) 'flicker' (i.e. flash on and off very rapidly). Compact fluorescent lamps (CFLs) flicker at a rate of more than 20,000 times per second, modern linear fluorescent tubes at a rate of more than 5,000 times per second and older style linear fluorescents at 100 times per second. These rates of flickering are not detectable by the human brain (studies suggest that 1% of people can detect a flicker rate of up to 60 times per second). If a linear fluorescent light has a noticeable flicker it is likely to have developed a fault and should be replaced. If a CFL has a noticeable flicker it could be the result of a poor quality product or may occur in situations where the lamp has been incorrectly fitted e.g. with an incompatible dimmer switch, in a touch lamp or some other electronic device.

LED light sources (lamps and integrated luminaires) have a completely different behaviour in terms of temporal light modulation. LED can respond very rapidly to variation in electrical supply. This means that the ensuing temporal light variation is completely dependent on the LED driver design and waveform of the electrical power delivered to the LED chip. Some LED lighting products display no flicker at all, whilst others display extreme TLM where the LED source effectively turns off and on very rapidly.

2.2.7 Reflector (Directional) Lamps

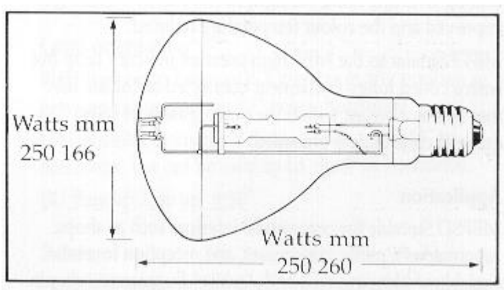
Reflector lamps are designed to perform without the need of an additional reflector (which would normally be built into a luminaire). In assessing the performance of reflector lamps we need to know the extent to which they distribute their light. This is measured in terms of:

- Beam angle
- Illumination levels
- Polar distribution (candela values in a particular direction)

Typical reflector lamps:

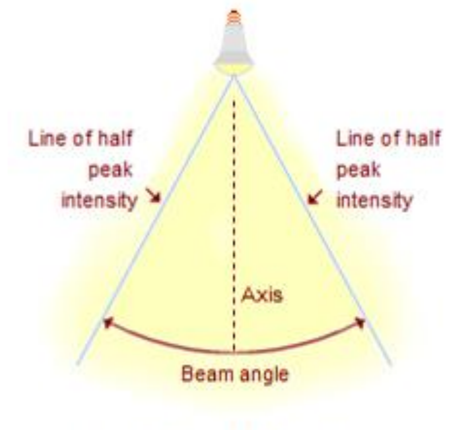
Incandescent PAR lamp

MR16 (Dichroic) lamp



Mercury Vapour Reflector Lamp

2.2.7.1 Beam angle



Beam angle of a reflector lamp

A beam similar to that of a torch is emitted by reflector lamps. This beam is usually shown accompanied by a 'beam angle' in degrees. This is a guide as to how light from the beam is concentrated or spread out.

Some lamp types are manufactured with a variety of beam angles. Lighting designers take advantage of this to tailor lighting schemes.

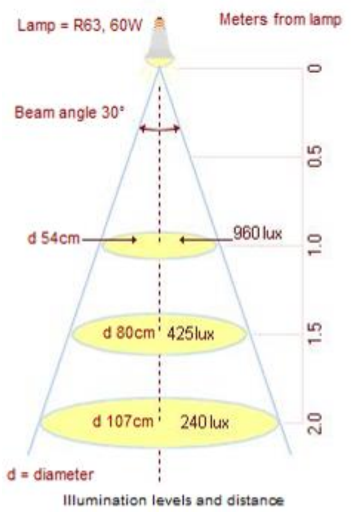
The beam angle is decided first by knowing the value of 'peak intensity'. Peak intensity is quoted in candelas and measured in front of the lamp on an imaginary line called the axis, which usually runs directly through the centre of the lamp.

To one side of the axis the luminous intensity gradually diminishes. The line at which the intensity has diminished to half is called the line of half peak intensity. The line of half peak intensity is also measured for the other side. The angle between the two lines of half peak intensity is the beam angle.

LEDs, being an inherently directional light source (i.e. installed on a printed circuit board) now represent a viable, efficient replacement alternative for most incandescent and halogen reflector lamps. Beam angles and polar distributions still apply to directional LED lamps. An example of a directional LED lamp is shown in the figure below.

2.2.7.2 Illumination levels

Published beam angle diagrams for reflector lamps also show illumination levels. These are shown as circular patches of light whose diameters and illumination levels are quoted at various distances from the lamp; a common way of showing the output of a low voltage tungsten halogen lamp (Dichroic or MR16).



There is a simple relationship between luminous intensity (cd) and illumination (lux):

Lux = candelas (cd)/distance in metres squared (m^2)

Example:

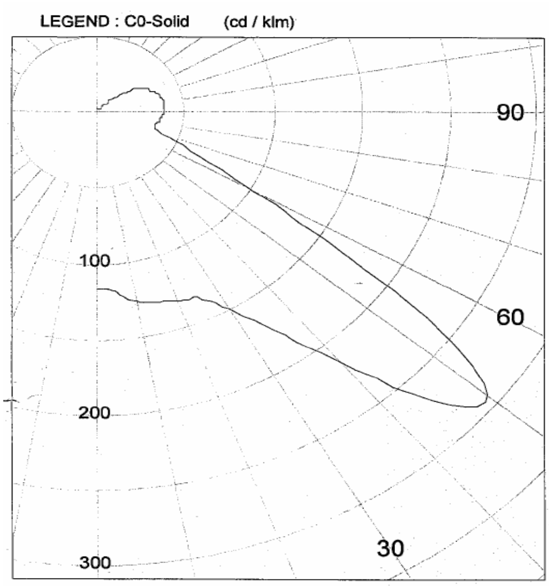
A reflector lamp with a peak intensity of 1,800 candela, is used to illuminate a jewellery display from a distance of 3 metres. The illumination level on the display will be:

1,800cd/3 m^2) = 1,800/9 = 300 lux

2.2.7.3 *Polar distribution*

Polar distribution diagram, also called a polar curve, is a graph showing how luminous intensity values vary with increasing angles from the imaginary axis of the lamp.

It is sometimes customary to show the curve for only one half of the distribution because in nearly all cases the other half would be an exact mirror image (i.e. the polar curve is symmetrical about the lamp axis).
An example of a polar distribution curve and the intensity table from where it is derived, is show below.



INTENSITY DATA (cd / klm)

Gamma	C0	LMS.	Gamma	C0	LMS.
0	117		90	38	
5	119	12	95	39	42
10	127		100	39	
15	130	37	105	38	40
20	132		110	36	
25	135	64	115	34	34
30	150		120	31	
35	175	112	125	27	24
40	214		130	21	
45	268	204	135	14	11
50	290		140	8	
55	205	180	145	5	3
60	103		150	4	
65	59	62	155	3	2
70	38		160	3	
75	34	37	165	3	1
80	35		170	3	
85	37	40	175	2	0
90	38		180	2	

2.2.8 Measuring light levels

There are three commonly used methods of measuring light levels:
- Detectors
- Illuminance meters (light meters)
- Luminance meters

2.2.8.1 Detectors

The most common type of detector used today is the solid state detector. There are several types incorporating semi-conductor materials which work from ultraviolet through the visible spectrum to infrared. Most of these work in what is called the photovoltaic mode where the short-circuit current is measured. They have the advantage that they are very linear over 10^{10} range, have a very fast response when used with no smoothing/averaging capacitor (creating a long time constant) and are not greatly affected by temperature (but are most accurate when operated near the calibration temperature, which is typically 23ºC). In order to measure “visible” light a specially matched filter must be used so that the light measured is the same as that seen by the human eye. That is the detector with filter has a photopic response.

2.2.8.2 Illuminance meters

Illuminance meters are the most common type of meter. They collect light over a full half hemisphere. They may receive light from several ‘sources’ at one time so the detector must have a good cosine response. The reading can also be affected by stray light. Well matched photopic filters and good cosine response diffusers are generally the difference between an inexpensive photometer and a good photometer. The inexpensive photometers generally don’t have any photopic filter and have cosine diffuser which have poor performance when the light source is at high angles of incidence (typically above 70º from the normal to the photometer). Inexpensive photometers are acceptable for comparative type measurements where the light sources have very similar spectra or transmissive or reflective materials don’t alter the spectrum of the light being compared.

Photometers need to be calibrated by a photometric laboratory approximately every 12 months in order to maintain their correct reading. Re-calibration is required mainly due to drift in electronic components within the meter.

2.2.8.3 Luminance meters

Luminance meters have the same elements as illuminance meters but also need an optical system to view the object of interest and image it onto the detector in a similar way to a telescope with collimating lenses at the front. Luminance meters can have a range of apertures to define the measurement field, the angle of which can be <1º to 10º. More sophisticated (and expensive) luminance meters include colour filters for measuring the colour (and colour temperature) of the object as well as its’ luminance.

2.3 Reflection, Transmission & Refraction

2.3.1 Reflection

In lighting design it is also necessary to consider the reflective properties of the surface being illuminated. When light strikes an opaque surface - and by opaque we mean a surface that will not transmit light - some of the light is absorbed and some is reflected. The ratio of the luminous flux reflected, to the luminous flux received, is known as the REFLECTANCE. If a small element of a surface receives 1000 lumens and reflects 700 lumens, then the reflectance is 0.7. Or it can be expressed as a percentage as 70%. The remaining 0.3 or 30% would be absorbed.

Different surfaces also reflect light in different ways. For example, surfaces such as paper, emulsion paint, carpets and so on, exhibit what we call matt or DIFFUSE REFLECTION. That is, the light reflected from the surface is scattered equally in all directions.

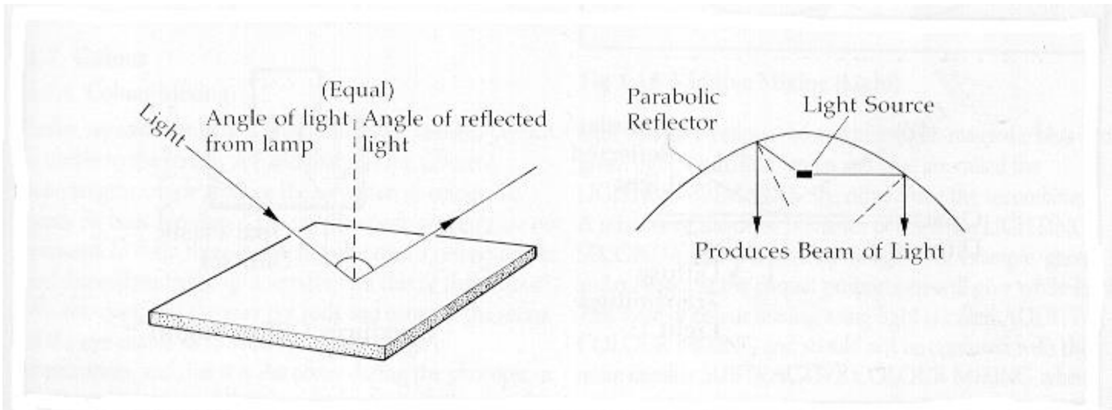
2.3.2 Specular Reflection

At the other extreme is mirror or SPECULAR REFLECTION exhibited by shiny metal surfaces such as chrome, silver or pure aluminium.

It is most important to realise that although specular reflections produce a clear image in the surface of the material, the actual amount of light reflected may be deceptively low. A matt white painted surface for instance has a reflectance of 75% to 80% compared with only 60% specular reflectance from a polished stainless steel surface. Many surfaces such as gloss paint, wood, plastic and so on, exhibit a combination of these two types of reflection. Gloss paint, for example, scatters most of the light that it reflects, but also produces a specular reflection in the surface of the paint.

In lighting design it is important to measure and assess the reflectances of the main surfaces of a room because they will reflect any light that falls onto them and increase the illuminance within the space. Colour charts exist that have reflectances marked on them and matching these with the surfaces of the room will give a guide to the reflective properties of the surfaces.

The reflective properties of surfaces are used by the control of light from light sources, and luminaires. (The international name, LUMINAIRE is often used instead of light fitting or fixture). Specular reflection occurs in smooth polished surfaces, such as mirror glass or polished aluminium. For any ray of light that strikes the specular surface of a reflector, the angle of incidence is equal to the angle of reflection.



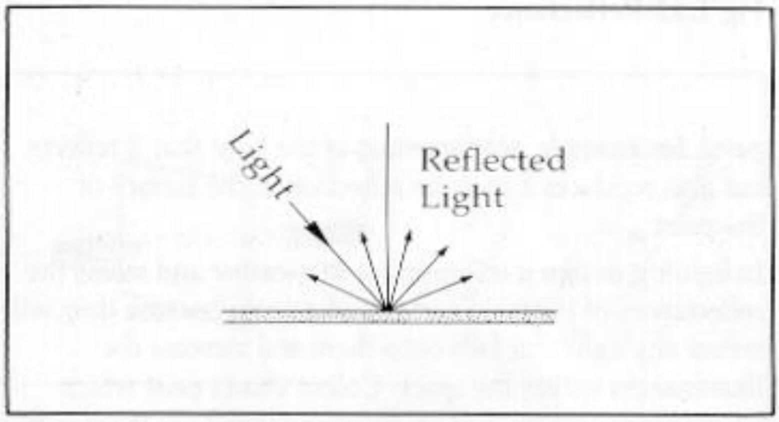
Specular Reflection

This principle still applies to each part of a specular reflector regardless of its shape. Practical specular reflectors are often curved or a series of flat facets. The degree of optical control will depend upon the size of the source relative to the reflector; how much light from the lamp the reflector collects and the degree to which the reflective material will scatter light (i.e. non mirror reflection). For example, compact low voltage tungsten halogen display lamps with integral mirrors (MR16 Lamps) use facetted reflectors. The overall shape of the reflector is approximately parabolic to give a near parallel beam. Because the lamps have a compact filament, precise beam control can be achieved with a small reflector.

A basic rule of thumb for reflector design is that the reflector must be 5 times the size of the light source to provide accurate beam control.

2.3.3 Diffuse Reflection

DIFFUSE REFLECTION occurs in matt surfaces and scatters light uniformly in all directions. Matt surfaces therefore appear equally bright from any direction of view and, in fact, this is the definition of a UNIFORM DIFFUSER. A diffusing reflecting surface will scatter light without producing a clear image of the source. The interiors of most luminaires use matt white diffusing paint because this is the most efficient way of reducing the light being absorbed in the fitting and increasing the output.



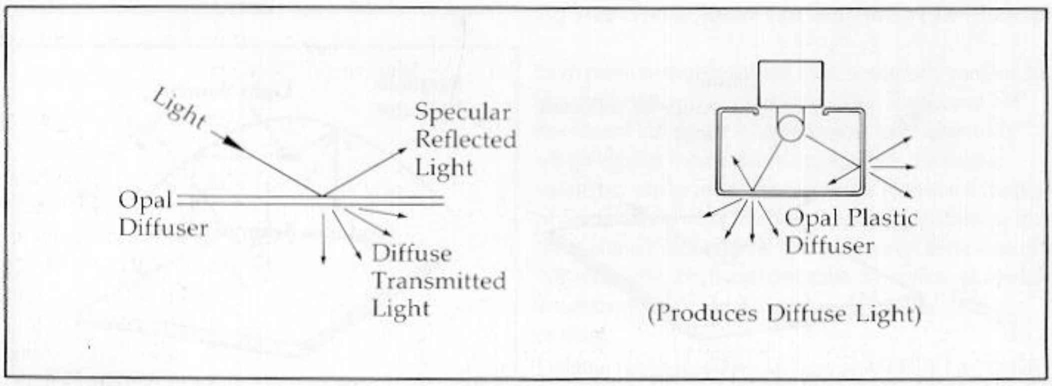
Diffuse Reflection

2.3.4 Mixed Reflection

Some surfaces show a mixture of a diffuse and specular reflection. For example, the bodywork of a car would look shabby if it did not provide both types of reflection. A specular image of the sky will be produced in the paint surface, yet most of the light will be reflected in a different manner by the pigment to produce the car's colour.

2.3.5 Transmission

Certain materials have the ability to transmit and diffuse light. This principle is known as diffuse transmission and occurs with opal glass and opal plastic diffuser luminaires. When a ray of light falls on translucent (light transmitting) opal material, some light is reflected specularly and some light passes through the material. This light is scattered or diffused, thus spreading the brightness of the bare lamp over a larger area. The area of illuminated brightness is therefore enlarged and for a given number of lumens coming from the luminaire, the lumens per unit area or candelas per unit area, are reduced which in turn reduces the brightness, i.e. glare from the luminaire is reduced. The amount of light that is emitted from a material, after passing through it, as a fraction or percentage of the light falling on the material is called the TRANSMITTANCE.

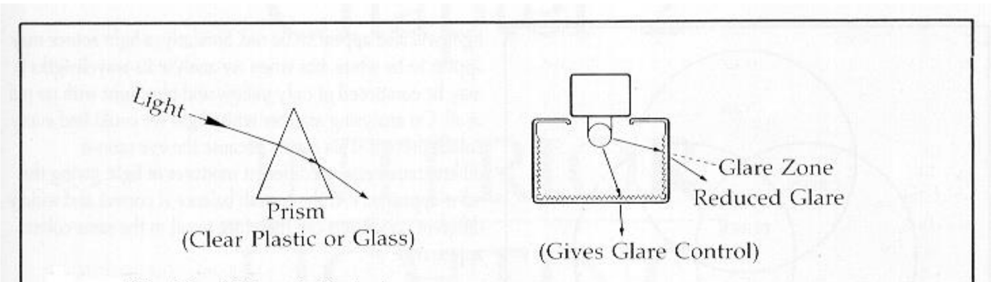


Diffuse Transmission

2.3.6 Refraction

When light passes from one transparent medium to another of different density, it bends, this is known as REFRACTION, e.g. air to glass, the light bends towards the perpendicular to the surface. When light passes from a dense to a rarer medium, e.g. glass to air, the reverse occurs. If light is passed through a triangular glass prism, it is deflected from its original path. Prisms, in glass or plastic can be designed to control light. Plastics are used extensively in prismatic controllers for both interior luminaires and street lighting lanterns.

The prismatic attachments for interior luminaires consist of a series of prisms designed to redirect the light away from the glare zone down onto the work area. This has the effect of both reducing direct DISCOMFORT GLARE and producing a more efficient light distribution, because more lamp lumens are directed downwards on to the work area. Prismatic attachments although clear, will absorb some light, but the losses are much less than for an OPAL DIFFUSER which may absorb up to 25% of the lamp lumens.



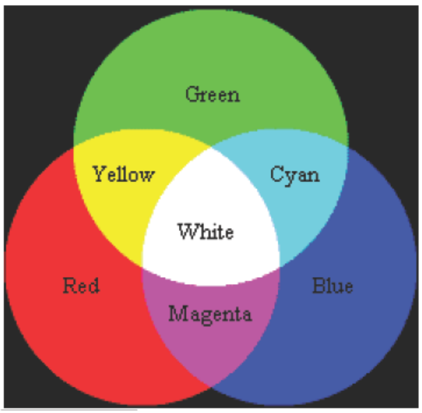
Principle of Prismatic Control

2.4 Colour

The three primary colours are red, green and blue. They are called primary colours because the colour sensitive components of the retina (the cones) are sensitive to red, green and blue. Any other colour can be derived from a combination of the three primary colours.

When the brain processes the signals from the retina of the eye, it collates and processes the individual light colours received by the eye into the colour actually seen. For example, if red and green light is focused on the retina, yellow light is seen. If blue and red light is focused, then violet (magenta) is seen etc.


The primary colours. Other colours can be derived from red, green and blue.



Note: Red, green and blue are the primary colours for light. The primary colours for paint and inks are red, blue and yellow.

2.4.1 Colour and objects

We see objects because of the light reflected from them. Objects reflect only their own colour, and absorb all other colours falling upon them. For example, a red post box appears red because it absorbs all colours other than red, which it reflects.

When light passes through an object all colours are absorbed, except for the colour of the object itself. An example is a blue lamp. When light from a lamp filament passes through its blue glass bulb, all colours apart from blue are absorbed. The blue glass does not convert all the light to blue, as is often thought.

2.4.2 Colour in relation to lamps

Natural sunlight (daylight) contains all the colours in the visible spectrum. However, this is not true for all lamps.

Lamps have two properties which describe their colour performance:

1. **Colour appearance** describes the colour the lamp appears to be when lit, or the general ambience of the light it provides.

2. **Colour rendering** indicates to what extent its light is capable of making objects appear their true colour.

2.4.3 Ultraviolet radiation

Just beyond the violet end of the visible range of the electromagnetic radiation spectrum is ultraviolet radiation. This radiation occurs naturally from the sun. It affects pigments and is responsible for colour bleaching and sun-tanning of the skin.
Ultraviolet (UV) is also artificially created in small amounts by all light sources, usually as an unwanted and mostly harmless by-product. However, some products are designed to produce UV, examples being sun-bed tubes and lamps for curing plastics and erasing certain types of computer micro-chip.

2.4.4 Infrared radiation

Just beyond the red end of the visible electromagnetic radiation spectrum is infrared (IR), which is heat. Like UV, infrared occurs naturally from the sun and is created to a greater or lesser extent by all artificial light sources. All lamps except LEDs give out more energy as infrared than they do as visible light.

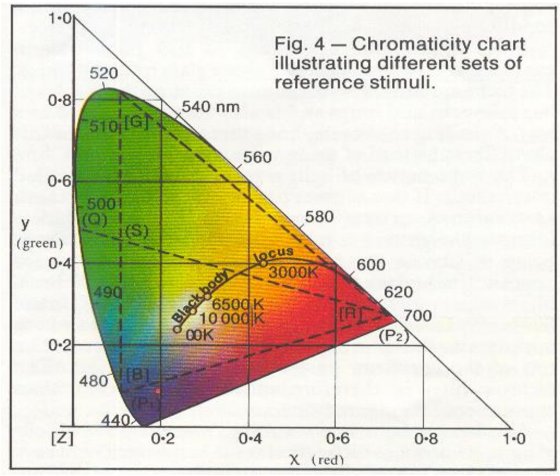
Some halogen lamps are designed to redirect the infrared content of their output, so that less heat is directed onto users or displays. This is the purpose of the dichroic coatings on some lamps. These lamps are said to give a cool beam or cool light, because the dichroic coating reduces the heat in the beam by up to 66% (this removal of heat should not be confused with colour temperature or colour appearance).

2.4.5 Colour Appearance / Colour Temperature

Colour appearance describes the ambience that a lamp provides, i.e. how 'warm' or 'cool' the light from a lamp makes the room feel. The lighting industry has adopted terms like 'Warm White' and 'Cool White' to describe this effect.

However, in practice, colour appearances of lamps can be difficult to judge. Sometimes, particularly with fluorescent tubes, colour appearance can be assessed by looking at the lamp which will appear 'cold' or 'warm' in line with the light being emitted. Other light sources are too bright to look at directly.

In these cases it is best to assess the colour appearance by illuminating a white background. From a design perspective, it should also be noted that the ambience of a room can also be due to decor, rather than lighting. Because the terms 'warm' and 'cool' are associated with temperature, a more technical description of a lamp's colour appearance is it’s colour temperature.



CIE Chromaticity Chart

The colour temperature of a light source is the temperature of a "black body" radiator having the same colour appearance. If we heat a tungsten filament it ‘glows’ red hot. The hotter it becomes, the whiter it becomes to the extent that the hottest objects have a bluish white appearance. The usual temperature scales of Celsius (°C) and Fahrenheit (°F) are not used for colour temperature measurement. Instead, the more scientific 'absolute temperature scale', which is measured in Kelvin is used. Kelvin is not quoted in degrees or °K, but simply K or Kelvin. The unit ‘size’ of the Kelvin and Celsius are the same. Water freezes at 0ºC and boils at 100ºC. The equivalent Kelvin temperatures are 273.16K and 373.16K.
The warmer a lamp (or light emitted from it) appears, the lower its colour temperature. The cooler (bluer) it appears, the higher the colour temperature. This is the opposite of heat measured on a thermometer. For example, a typical GLS incandescent lamp produces much of its light in the red wavelengths, giving it a 'warm' yellowish appearance, but its colour temperature is low, only around 2,700K whereas a daylight fluorescent tube having a high colour temperature (6,500K) has a cool bluish appearance because it produces more of its light in the blue wavelengths. General classifications of colour appearance and temperature:

Colour temperature	Colour appearance
<3,300K	Warm
3,300 – 5,300K	Intermediate
>5,300K	Cool

2.4.6 SDCM

SDCM stands for Standard Deviation of Colour Matching. It refers to how different a lamp’s colour is from the ideal colour given by it’s rated (claimed) colour temperature.

A lamp model has a rated colour temperature in Kelvin, which should be one of the six standard values in column 1 of the table below (2700K, 3000K, etc.).

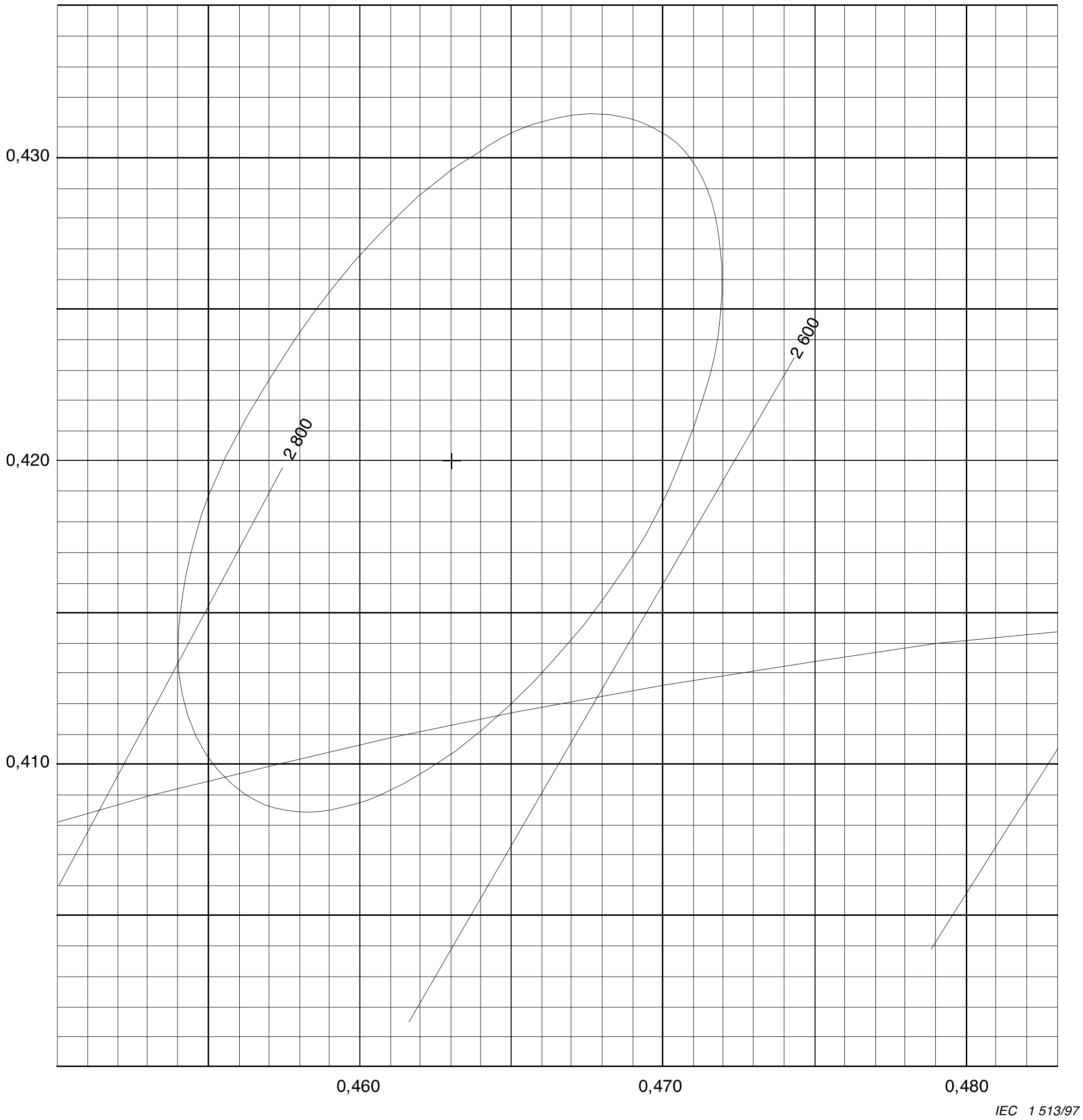
Each of these six colour temperatures have standardise chromaticity co-ordinates (x, y) where x and y are values on the CIE Chromaticity Chart (see figure above). The standard x and y coordinates for the six colour temperatures are given in international standard IEC 60081 and appear in the table below.

"Colour"	T_c	*x*	*y*
F 6500	6400	0,313	0,337
F 5000	5000	0,346	0,359
F 4000	4040	0,380	0,380
F 3500	3450	0,409	0,394
F 3000	2940	0,440	0,403
F 2700	2720	0,463	0,420

For a given lamp sample with a given rated colour temperature (say 2700K) the SDCM is a measure of how far away that sample's x and y co-ordinates are from the Standard Chromaticity Co-ordinates for 2700K (for 2700K these are x=0.463 and y=0.420 from table above).

The "how far away" is given as an SDCM value (for each sample). A low SDCM value means the sample has x, y co-ordinates which are close to 0.463, 0.420 in this example. A high SDCM value means they are far away.

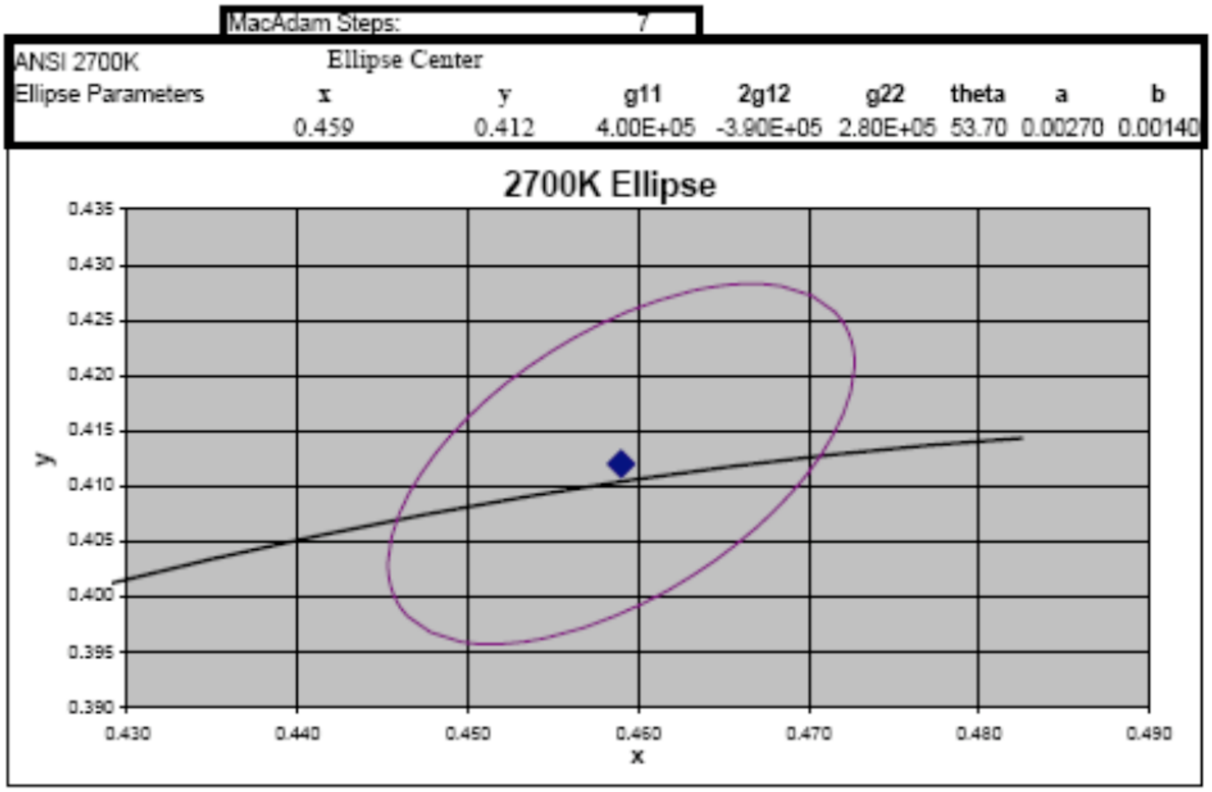
The SDCM shape is actually an ellipse on the x, y plot. For example, if the sample's SDCM value is 5 (or less), then its x and y co-ordinates sit on (or within) the 5-step MacAdam ellipse depicted in the IEC figure below.



x = 0,463 *y* = 0,420

Figure D.6 – Tolerance area for standard "colour" F 2700

If the sample's SDCM value is 7 (or less), then its x and y co-ordinates sit on (or within) the 7-step MacAdam ellipse depicted in the figure below (from Energy Star).



A colour difference of 3 SDCM is just noticeable to the human eye. In other words, a lamp sample with an SDCM of 3 can just be differentiated from the "perfect" lamp with colour exactly as claimed (e.g. 2700K with x and y co-ordinates of 0.463 and 0.420 respectively.

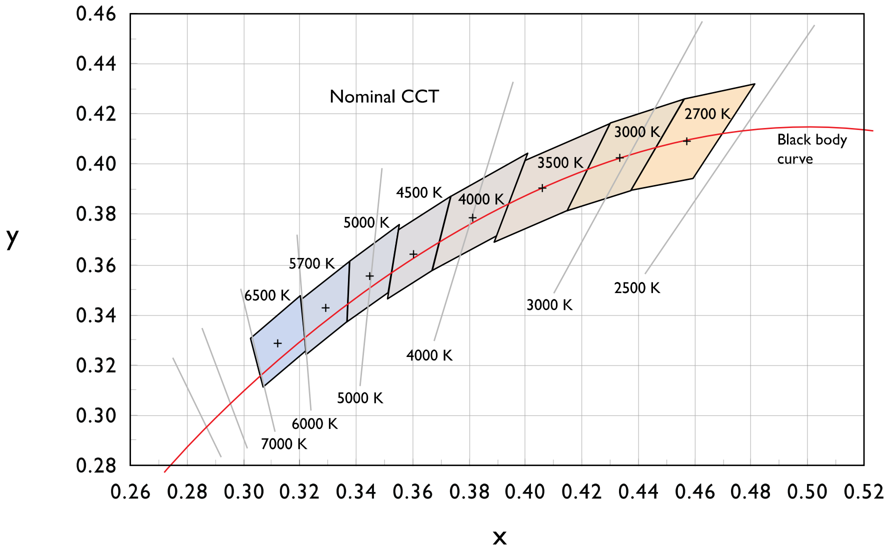
2.4.7 Duv

Duv is a more recent method for measuring the colour discrepancy of a lamp, i.e. how far away it falls from the perfect match for colour temperature.

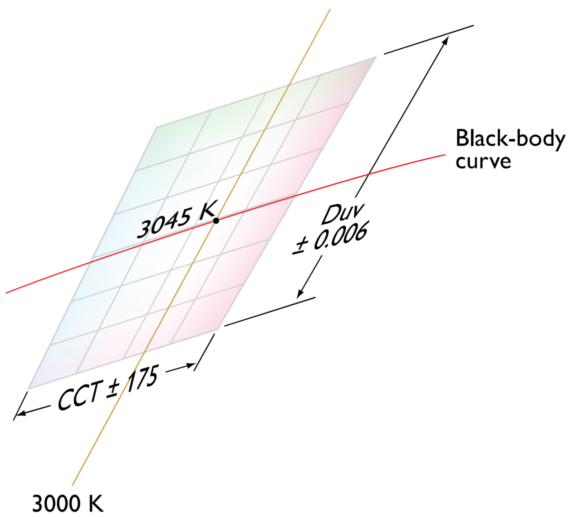
Variations along the black-body curve (see figure below) are measured in degrees K, while variations perpendicular to the black-body curve are notated as Duv. Duv ranges are defined on the CIE 1976 colour space, rather than the 1931 colour space, because the 1976 colour space (also known as the CIELUV colour space) is better suited for evaluating colour differences of light sources. It uses a uniform scale in which a distance measured anywhere on the colour space represents the same degree of difference in colour.

The axes of the CIE 1976 colour space are u' and v', instead of x and y. Duv measures the distance from the black-body curve, and therefore the degree of colour change (its delta). Positive Duv values are above the curve, while negative Duv values are below the curve.

As the diagram below shows, allowable variations both along and perpendicular to the black-body curve define a quadrangle within the colour space for each colour temperature.



The figure below shows a Duv of ± 0.006.



2.4.8 Colour Rendering

The extent to which a light source is capable of making objects appear their true colour is known as colour rendering and it is determined by the **spectral power distribution** or spectrum of the light source. Only those colours that fall onto a surface can be reflected from it. For example, when buying an item of clothing, people instinctively take it close to a window as they know that it will make it appear its true colour, without distortion. In other words, daylight has excellent colour rendering ability.

Lamps vary in their ability to render colours correctly. For example, incandescent lamps emit all colours of the spectrum. Therefore they will render almost all colours accurately. On the other hand, low pressure (SOX) sodium lamps give out nearly all their light in the yellow/orange part of the spectrum, so will only render yellow/orange colours properly. Other colours appear dull and lifeless under SOX lighting. Low pressure sodium lights are often chosen for tasks that do not require good colour rendition, such as security, roadway and tunnel lighting, because of their high efficacy.

2.4.8.1 The CRI or Ra scale

The colour rendering ability of lamps is measured on the Colour Rendering Index (CRI) or Ra scale (pronounced ar-ray). The scale ranges from 0 to 100, where lower values indicate poor colour rendering and higher ones good colour rendering. One hundred being as good as a black body radiator of the same colour temperature.

To make comparing the colour rendering qualities of light sources easier, the Australian Standards (based on CIE international standards) group the Colour Rendering Index (CRI or Ra) for lamps as shown below:

Group	CRI or Ra value	Colour rendering
1A	90 - 100	Excellent
1B	80 - 89	Very good
2A	70 - 79	Good
2B	60 - 69	Fairly good
3	40 - 59	Acceptable
4	20 - 39	Poor

Typical CRI or Ra figures for the various lamps are:

- Incandescent 100
- Tungsten Halogen 100
- Fluorescent (halophosphor) 60+
- Fluorescent (triphosphor) 80+
- Compact Fluorescent (CFL) 80+
- Specialised Fluorescent (enhanced CRI) 90+
- Standard Quartz Metal Halide 65
- Ceramic Metal Halide 80+
- Standard Mercury Vapour 45
- High Pressure Sodium 25
- White High Pressure Sodium 60
- Low Pressure Sodium 15
- Light Emitting Diode (LED) 75+

As discussed in the following section, the existing CRI scale is not always useful for LEDs.

2.4.8.2 New Colour Rendering Index for LEDs

The colour rendering index (CRI) has been used to compare lamps for over 40 years but the International Commission on Illumination (CIE) have stated that "*the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set*". This recommendation is based on a survey of numerous academic studies that considered both phosphor-coated white light LEDs and red-green-blue (RGB) LED clusters. Most of these studies involved visual experiments where observers ranked the appearance of illuminated scenes using lamps with different CRIs. In general, there was poor correlation between these rankings and the calculated CRI values. In fact, many RGB-based LED products have CRIs of 20 to 30, yet the light source appears to render colours well. The figure below shows how the spectrum of LEDs differs from other light sources

At the time of writing of this manual, the CIE were expected to produce a new test method for CRI, which is expected to compare, using spectral distribution analysis, how well a test light source renders a set of colour samples, compared to a reference light source. However, it should be recognised that this is a highly contentious area and that, at the time of writing, CRI remained the sole metric for assessing colour rendering.

Figure 1

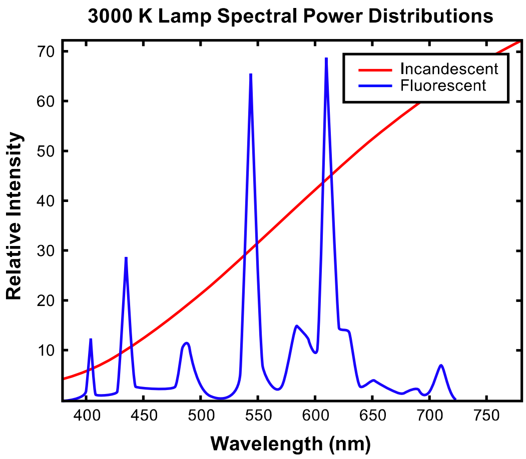
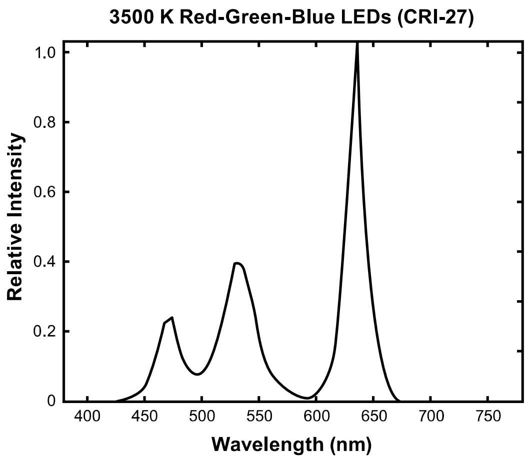
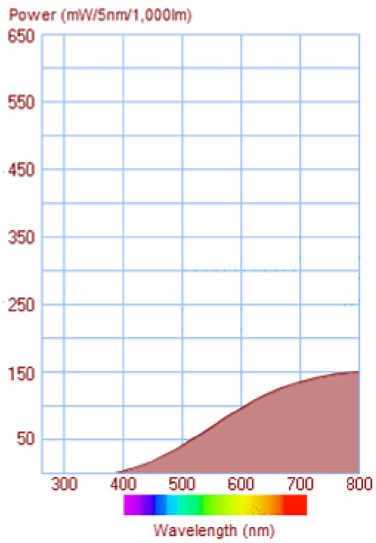


Figure 2

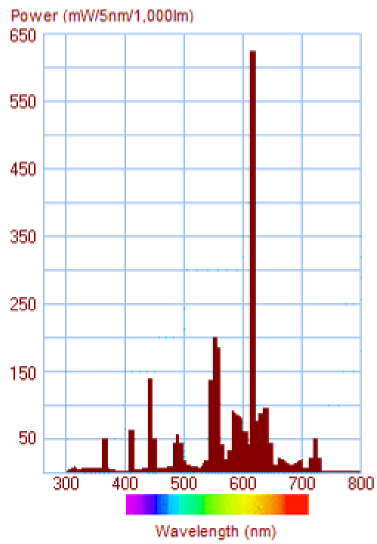


2.4.8.3 Spectral power distribution

The colour rendition of a lamp (and hence its CRI or Ra rating) is directly influenced by its 'spectral output'. It is conventional to show this as a graph.



Incandescent lamp



Fluorescent lamp

The graphs' two axes are power and wavelength. The wavelengths are shown in nm (nanometres) as usual. The power axis is known as 'radiated power', which is measured in Watts (W) or milliWatts (mW). In this graph the power is measured for a light output of 1000 lumens for every 5nm step, i.e. mW/5nm/1000lm.

The resulting line on the graph is called the Spectral Power Distribution Curve, and shows how power is distributed across the visible spectrum.

2.4.8.4 Continuous spectrum and line emission

As can be seen in the graph, the emission from incandescent lamps is radiated across all the wavelengths and blends smoothly from one wavelength to the next. This type of output is called 'continuous spectrum'.

In contrast, discharge lamps such as fluorescent tubes are designed to give out energy only at certain wavelengths, making the graph peaks erratic. This is known as 'line emission'. The colour rendering ability of discharge lamps is determined by the particular wavelengths of the energy emission.

2.4.8.5 Colour rendering – LEDs

White light LEDs can exhibit a very wide range of colour rendering properties, from poor to very high. This is primarily a function of the phosphors used to generate white light. Whilst LED colour rendering has improved in recent years, care should be taken to ensure that the LED chosen does have the desired ability to render colours.

As discussed above, the existing colour rendering index (CRI) may not suit all LEDs, although at the time of writing this was the only index available.

2.4.8.6 Colour rendering – Incandescent lamps

The lamps rely on the process of incandescence to produce light from a tungsten filament. (Incandescence is the emission of visible light from a substance or object as a result of heating it to a high temperature.) At a colour temperature of 2,700K, the filament emits light as a smooth continuous spectrum, producing a CRI or Ra value of 99, almost as good as that of a true black body .

2.4.8.7 Colour rendering – Fluorescent Lamps

The white appearance of an unlit fluorescent tube is due to the phosphor powder coating on the inside of the tubing. It is this coating which is responsible for most of the light, and the colour performance of the lamp once lit.

Basic fluorescent lamps are sometimes referred to as 'halophosphate' fluorescent tubes. They use a single phosphor belonging to the chemical family of 'halophosphates'. These lamps do not have good colour rendering abilities and are now unavailable in Australia due to their inefficiency.

Fluorescent lamps with better colour rendering use three additional phosphors, which has led to these tubes being called 'tri-phosphor' fluorescent tubes. Each of the three additional phosphors produces one of the primary colours of the spectrum, red, green and blue. The primary colours mix to produce a white light, which combined with the halophosphate phosphor, produce an improved balance of colour in the spectral output. The result is that the quality of the light produced is superior to tubes only coated with the single halophosphate.

2.4.8.8 Colour rendering – Discharge Lamps

High Pressure Mercury

Mercury lamps generate light from the excitation of mercury atoms by an electrical discharge. The light given off is a cold bluish/green colour which is deficient in red light. This gives them a relatively poor colour rendering value. However some mercury lamps have a golden brown filter coating which allows them to emit a similar light colour to that from an ordinary light bulb.

Metal halide (HCI and HQI)

These lamps are essentially high pressure mercury lamps with other chemicals added to the mercury to improve the balance of the spectral output. The HCI lamps incorporate ceramic technology whilst the HQI feature quartz technology. The chemical additions result in largely good colour performance.

Low pressure sodium (SOX)

These lamps use sodium to produce their characteristic orange light, which at a wavelength of 589nm is near that of peak eye response. These lamps achieve the highest efficiency of any light source (up to about 200lm/W), but they have the worst colour rendering of any lamp - because they are monochromatic.

High pressure sodium

These lamps use mercury and sodium together with Xenon (a gas) to produce light. The contribution of the bluish-green of the mercury produces a better spectral colour balance than that of SOX lamps. They produce a golden coloured light at around Ra25.

3 Choice of Light Source

This chapter discusses the various types of light sources that are available, how they work and their pros and cons, particularly with respect to their efficacy and, therefore, their contribution towards sustainability.

Note that "legacy lamps" - incandescent and halogen lamps - are described in detail in Appendix 3.

The diagram below summarises the main categories of light sources. A light source means a component designed to convert electricity into visible radiation. In most cases, except integrated LED luminaires, the light source is a "lamp" which can be removed and replaced at the end of its life.

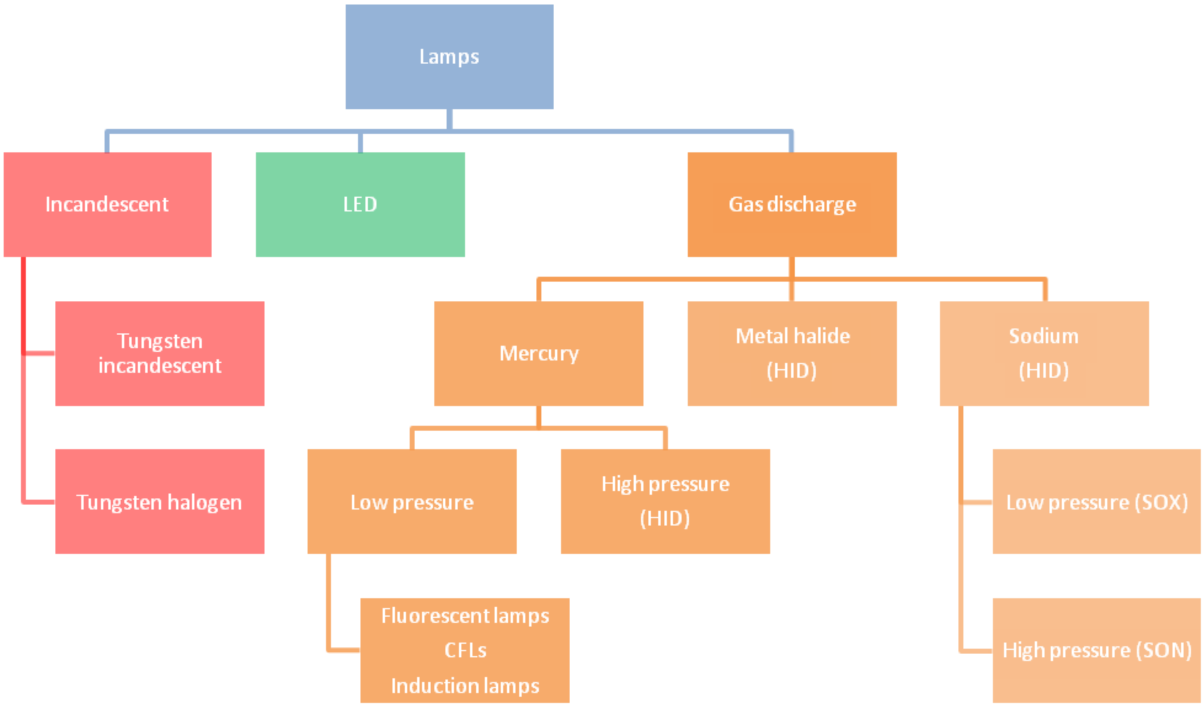
For the majority of new lighting installations, LED now represents the most efficient choice, and this trend is likely to continue well into the future. The other types of light sources (lamps) are covered in this chapter because they are still likely to be found in many homes and businesses.

HEADS UP: Light Source Choice and Energy Efficiency

Choosing the light source has an enormous impact on energy efficiency, although it is only one link in the design chain. It is possible to design a very inefficient lighting system, using very efficient light sources. As can been seen in the graph below, LEDs and gas discharge lamps are more efficient than incandescent and halogen lamps, and these filament-based lamps are now discouraged.

Low voltage halogen reflector lamps (dichroic lamps) have become very popular in the past 20 years and are marginally more efficient than tungsten incandescent lamps. However, from a design perspective, their highly directional light output makes them a poor choice for general purpose illumination, meaning that large quantities are required to light open spaces. LEDs now represent a far superior choice for directional lighting.

LEDs do however exhibit a range of efficiencies, thus great care should be taken in selecting LEDs for any lighting purpose.



It is worth noting that some LED luminaires now comprise an integrated LED-based light emitting element other than a replaceable LED lamp (i.e. LED packages, LED arrays, LED light engines) connected to the mains supply. These include integrated downlights, suspended and surface mounted, recessed, panels, battens, high-bay and low-bay LED luminaires.

The word “lamp” is the generic term for a device that creates light either by thermal emission or by discharge radiation. Light can be produced from electricity in many ways, of which the following are the most important in lighting engineering.

i. **Incandescence** or thermo-luminescence is the production of light from heat. Light from a filament lamp is produced in this way; electricity is used to raise the temperature of the filament until it is incandescent.

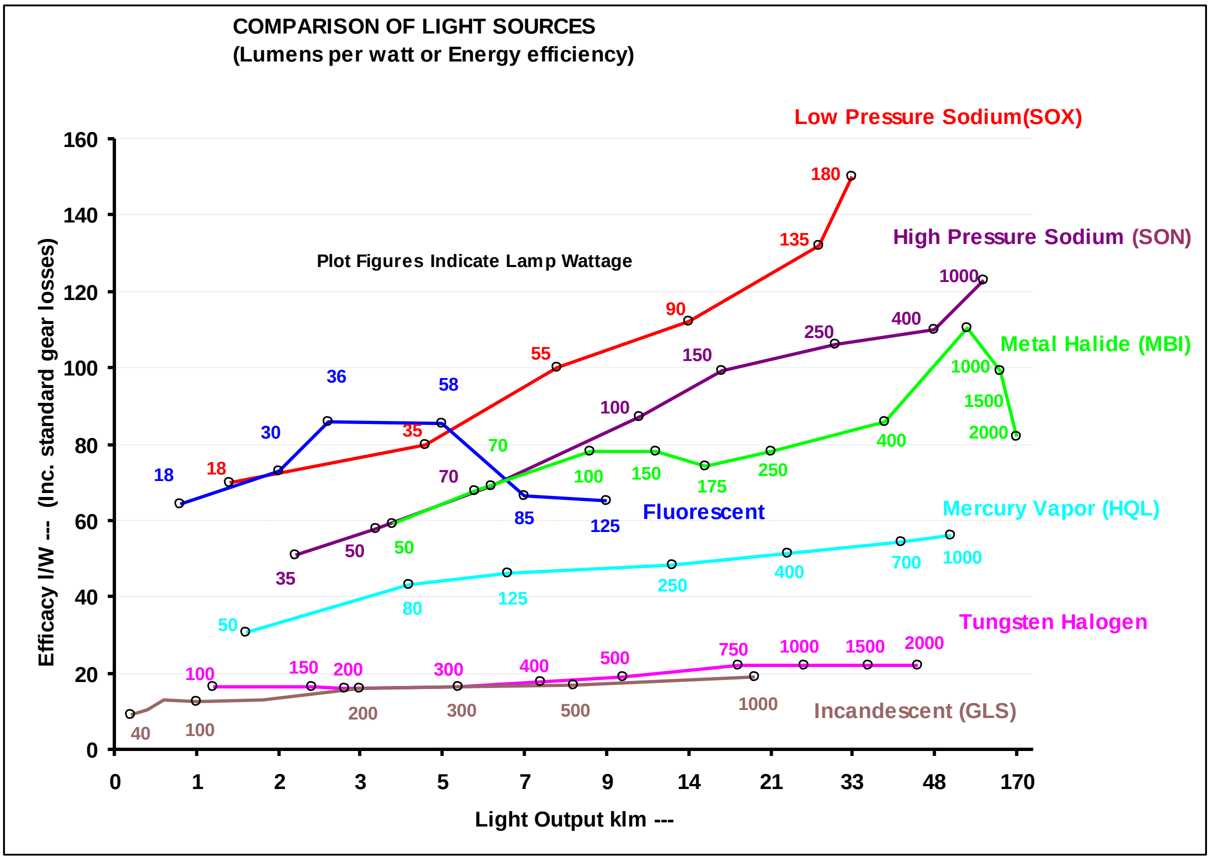
ii. **Electrical Discharge** is the production of light from the passage of electricity through a gas or vapour. In lamps using this principle the atoms of the gas are agitated or excited by the passage of the electric current and this atomic excitation produces visible radiation, ultra-violet and infra-red energy.

iii. **Phosphorescence & Fluorescence** are the processes of converting the invisible ultra-violet energy emitted normally from an electrical discharge, into visible light. Material called phosphors cause ultra-violet energy to make the transition into visible light.

iv. **LEDs**, or Solid State Lighting (SSL), use one or more semiconductor diodes (solid state chip) to emit non-coherent optical radiation. This radiation can either be in the visible spectrum (i.e. the LED directly produces visible light), or the visible light can be produced indirectly, e.g. with the radiation exciting phosphor which in turns emits the visible light in a similar way to fluorescence.

The efficiency of a lamp (also known as ***efficacy***) is measured in lumens per watt. The chart below shows the typical efficacy of the standard lamps including standard control gear losses. This allows the relative efficiency comparison of lamps to be made. As an example, a 100 watt incandescent lamp produces approximately the same amount of lumens as a 20 watt fluorescent lamp. Similarly, a 250 watt metal halide lamp produces approximately the same amount of lumens as a 400 watt mercury vapour lamp.

Not graphed below are LEDs, which have a broad range of efficacy. At the time of writing, high quality LEDs have an efficacy of at least 120 lumens per Watt, regardless of light output, and LEDs exhibiting efficacy of 200 lumens per Watt are predicted to be available in the near future.



3.1 LEDs

> **HEADS UP: LEDs and Energy Efficiency**
>
> LEDs are an emerging technology and are often claimed to be very efficient. In practice, products that use LEDs have a range of efficacies, thus great care should be taken when selecting LEDs for any lighting purpose.

Light emitting diodes (LEDs) are semiconductor devices that emit light. They have the potential for very long life (in excess of 50,000 hours) and very high luminous efficacy (> 200 lm/W). The individual diodes are compact and robust. As this technology is still being improved, no generalizations about performance can be made. Most currently commercialized LED products are intended for retrofit applications—they directly replace lamps of other technologies (e.g., incandescent). “Integrated” LED luminaires are also available, where the LED light source and all other components are integrated into a single, indivisible luminaire. LEDs can be used in entirely new ways and some manufacturers are developing innovative products that look, feel, and function differently from all incumbent technologies.

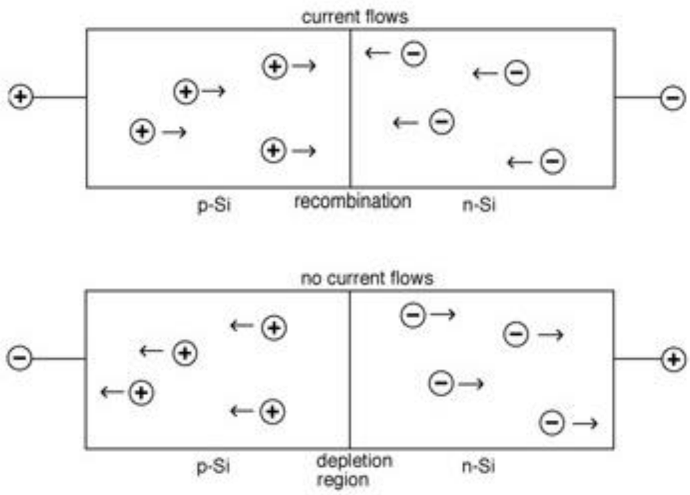
LEDs produce heat, but the heat is not significantly dissipated by radiative or convective transfer without intervention. Thermal management, the practice of preventing the junction of the LED from becoming too hot, is important to maintain stable luminous flux, chromaticity, and luminous efficacy.

LEDs operate very differently to filament lamps or discharge lamps, as they generate light via a process known as electroluminescence. This phenomenon was first observed in 1907 by H. J. Round experimenting with silicon carbide. In 1962, the first red LEDs were invented. By the mid-70s LEDs emitting light of a range of colours, including yellow, orange and green, had been developed. However, these early devices were not practical for lighting, with low luminous flux and efficacy.

Between 1970 and 1995, the luminous flux of red LEDs increased by a factor of approximately 45. Between 1995 and 2003, the efficacy of LEDs increased by an average factor of 16 and the luminous flux per LED package by a factor of 430. Improvements in efficacy and flux continue today, with each generation of new LED products showing performance improvements over their predecessors. Today, LEDs are widely used for certain niche applications, such as traffic lights and emergency exit signs, as well as for illumination applications, such as roadway and interior lighting.

3.1.1 Generation of Light

A light emitting diode (LED) is a solid-state device with the characteristics of a diode (i.e., electrical current can flow through it in one direction only) that generates light through radiative recombination. A negatively charged material (n-type) contacts a positively charged material (p-type) to form a p-n junction. Current flow causes electrons to move from n-type material to the p-type material and light is emitted. The two materials that form the p-n junction determine the spectrum of the light. These semiconducting materials are combined to create an LED die.



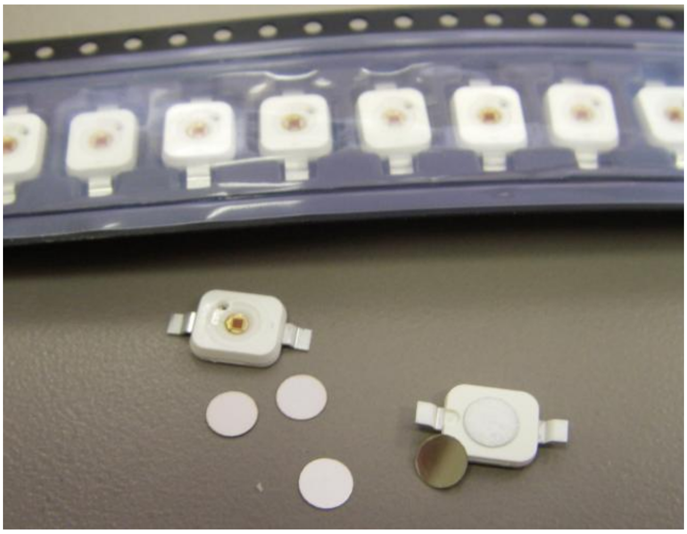
Typical LED p-n junction

3.1.2 LED Devices & Components

Commercial LED products are available for a multitude of purposes. Some will primarily be useful to a luminaire manufactures and must be combined with other components before they can be used for illumination applications. Others include all of the necessary components and can be used for architectural lighting without requiring modification. The terminology used in this section is consistent with IES RP-16-05.

3.1.2.1 LED Packages

After LED “dies”, the smallest functional unit of an LED product is an LED “package”. LED packages contain one or more LED dies and electrical connections. Other optical, electrical, mechanical or electrical components may be incorporated. LED packages cannot be directly connected to a mains electricity circuit. Currently, LED packages are supplied sealed into a plastic tape and wound onto reels.



Typical reel of LED packages

A distinction is commonly made between high-power and low-power LEDs. Though no formal definitions exist for these terms, LEDs rated for 1.0 W or more of electrical power are typically considered high-power, the type primarily used for illumination applications at the present time.

Typical high power LED packages

3.1.2.2 LED Arrays/Modules

An LED array or module is an assembly of LED packages or dies on a substrate, usually a printed circuit board (PCB). Frequently, optics and other interfaces (e.g., electrical, thermal, mechanical) are included to allow the array/module to be connected directly to an LED driver.

3.1.2.3 LED Light Engine

An LED light engine is an assembly of LED packages and/or arrays/modules, electrical supply source to drive the LEDs (LED driver), and any optical, electrical, mechanical, or thermal components needed for operation. LED light engines usually use snap-on wiring harnesses to connect the driver to the rest of the engine at the present time. LED light engines are intended to be directly connected to a mains electricity circuit.

It is common for the mounting substrate the LED light engine to have a series of holes that allow attachment to a variety of heat sinks. Light engines do not incorporate conventional lamp bases.

3.1.2.4 LED Lamp

An LED lamp includes the same basic components as an LED light engine: LED packages and/or arrays/modules, LED driver, and all needed optical, electrical, mechanical, and thermal elements. However, an LED lamp also incorporates a conventional lamp base. Therefore, LED lamps are primarily developed for retrofit applications.

LED lamps and module products can be broken into three basic groups in relation to how they are connected to electrical power. This terminology can be applied to both lamps and modules:

- Integrated LED (LEDi)
- Semi-integrated LED (LEDsi)
- Non-integrated LED (LEDn) or (LEDni)

The International Commission on Illumination (CIE) Test Method for LED Lamps, LED Luminaires and LED modules, (CIE TC 2-71) defines an **integrated** LED lamp or module (LEDi) as an “LED lamp/module incorporating LED control gear, and any additional elements necessary for stable operation of the light source, designed for direct connection to the supply voltage”. Typical examples of this will be LED lamps which have a cap designed to be plugged directly into 240V power.

A **semi-integrated** LED (LEDsi) is defined as an “LED lamp/module which carries the control unit of the LED control gear, and is operated by the separated power supply of the control gear”. Examples include MR16, MR11 (with bi-pin bases GU5.3, GU4 respectively) which have an integrated driver and though they are attached to a transformer to step down 240VAC to 12VAC/DC, the transformer is not the driver, even though by its nature it restricts current flow.

A **non-integrated** LED lamp or module (LEDni) is an “LED lamp/module which needs separate control circuitry or LED control gear to operate”.

Omnidirectional-replacement LED

Directional LED lamp

LED MR16

Examples of integrated (left, middle) and semi-integrated (right) LED integral lamps

3.1.2.5 LED Luminaire

An LED luminaire is a complete lighting unit that generates light with LEDs (through the use of LED packages, arrays/modules, and/or lamps). All mechanical supports, electrical components to drive LEDs, thermal management, and optical elements to distribute the light are included.

LED luminaires are emerging as a cost effective non-directional and directional lighting solution for domestic and commercial applications.

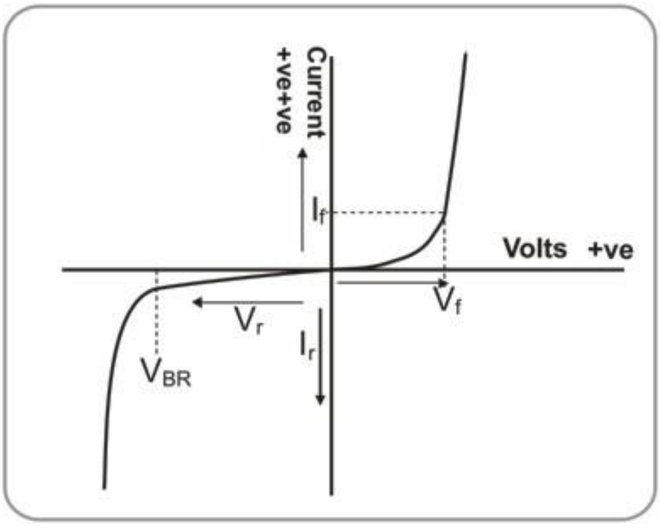
LED luminaires can replace traditional luminaires (that have lamp holders that potentially allow lamps of different technologies to be used). Purpose-designed LED luminaires provide the opportunity for better optical efficiency due to the removal of the physical size/shape, light distribution, and restrictions of traditional lamp classes (e.g. A19 shape lamp). However, this also means that, for some luminaires, the LED chip is an integral and permanent part of the luminaire (unless in module form) and any improvement in energy efficiency of the luminaire requires the replacement of the entire luminaire, at a higher cost than the replacement of a non-integrated lamp (this would be expected to occur at the end of life, which is typically declared as greater than 25,000 hours of operation).

Example of integrated LED luminaire

3.1.3 Operation

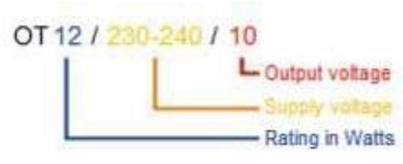
At present, most LEDs require low-voltage direct current (DC) power for operation. Though LEDs that use alternating current (AC) do exist, they are far less common. Therefore, the power for LEDs must come from an appropriate driver or power supply. While integrated LED products (e.g., luminaire) included all electrical components, external electrical sources are needed to drive LED packages or modules/arrays.

LEDs have a very non-linear relationship between current and voltage. Because of this, a relatively small change in voltage can induce a comparatively large change in current. Therefore, constant-current power supplies typically drive LEDs. Manufacturers often specify the typical and maximum current and/or voltage at which their products should be operated.



Typical LED I-V (current-voltage) curve

Taken from Osram material, this is a typical naming convention for an LED driver;



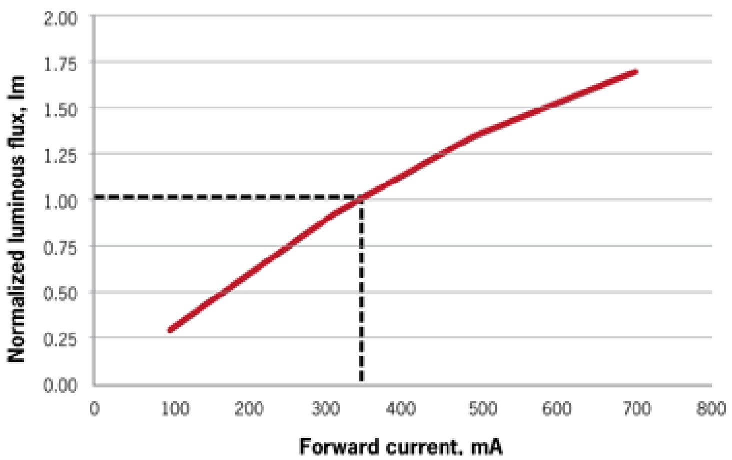
The output voltage in the naming system above is sometimes followed by one or two characters, which denote the case style (E for external use, CE for compact external, L for long, S for square).

Currently, the most common thermal management technique for LED light engines, lamps, or luminaires involves the attachment of LED dies, packages or modules/arrays to aluminium heat sinks. These pieces of aluminium conduct the heat away from the LED and it is dissipated by convection on the surface of the heat sink. These heat sinks can be bulky and heavy. Some research is underway investigating the feasibility of using thermally conductive plastics as heat sinks, to minimize the weight of LED luminaires. Other thermal management techniques include the use of fans or even circulating water. These methods may introduce noise and can limit the lifetime of the system.

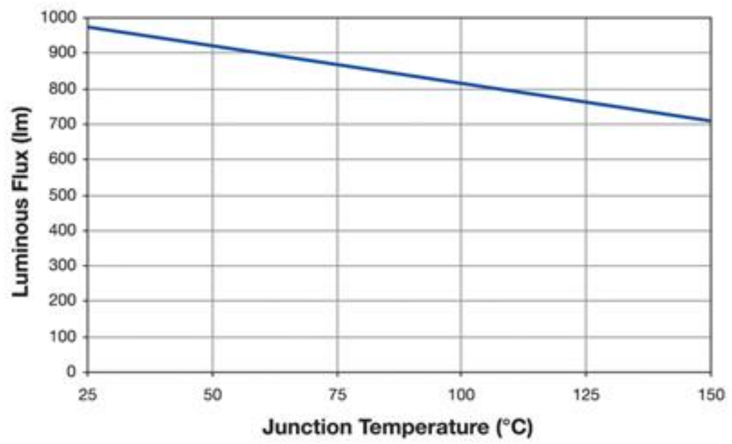
3.1.4 Efficacy

Not all of the light produced at the p-n junction escapes from the LED die. Some light is reabsorbed by the semiconducting materials or other components in the die and converted to heat. The luminous efficacy of LED dies has been steadily improving in recent years and improvements are expected to continue.

LEDs suffer from a phenomenon called droop. Droop can be divided into two types: current droop and thermal droop. Current droop refers to the finding that the luminous efficacy of LEDs decreases as electrical current is increased. The causes of current droop are not fully understood, but this is a topic of much research. Thermal droop refers to the fact that the luminous efficacy of LEDs decreases as the temperature of the p-n junction increases. Furthermore, increased junction temperature can reduce the lifetime of LEDs and induced shifts in their spectral output. This is why thermal management is important for efficient, reliable operation of LEDs.



Typical LED luminous flux as a function of current



Typical LED luminous flux as a function of temperature

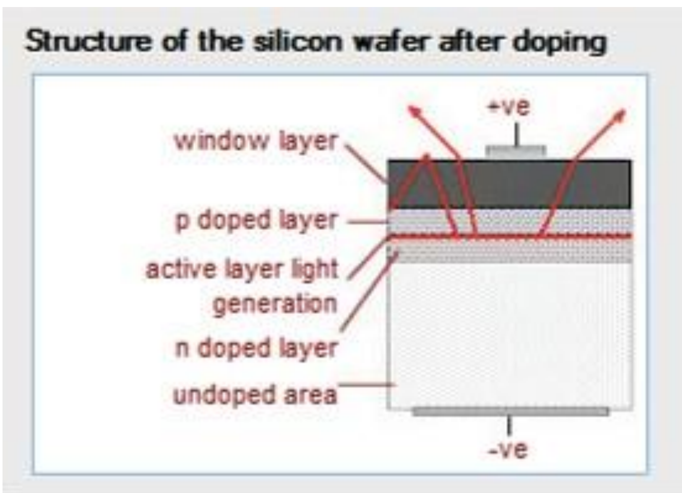
As with all lighting technologies, the spectral output of any given LED will impact its luminous efficacy. LEDs with spectral power concentrated near the peak of the Spectral Luminous Efficiency Function will produce more lumens per radiometric watt of light than LEDs that emit light primarily in the very long or very short wavelengths.

The luminous efficacy of an LED light engine, lamp, or luminaire will depend on the way that all of the components of the product are integrated. LED drivers and power supplies introduce electrical losses and also generate heat. If placed too close to LED dies, packages, or arrays/modules (as is often required in a retrofit lamp), the heat can raise the LEDs' junction temperature. Due these types of interdependencies, absolute photometry is widely used for LED luminaires.

The efficacy of LED luminaires is rapidly improving. For the most part, they are more efficient than similar incandescent luminaires and are increasingly competitive without fluorescent alternatives. However, because many factors influence the efficacy of an integrated product that utilizes LEDs, designers must rely on photometric test reports to determine the efficacy of any particular LED luminaire, light engine, or lamp.

3.1.5 LED Manufacture

An LED die is manufactured in a wafer fabrication plant. In the plant, chemicals called dopants are passed over circular wafers of pure semiconducting material (the substrate) as gasses or liquids at high temperatures. Two different sets of dopants diffuse into the wafer to form two distinct layers with different atomic and therefore different electrical properties. The boundary between these two layers forms the p-n junction.



When the diffusion process is complete, the surface of the die can then be shaped to help light escape from it by masking and etching the surface. This is followed by the formation of a very fine metal pattern on the top of the die (metallisation), which will be used to carry electrical current.

Finally, the wafer is cut into individual LED dies and transferred to another facility (backend production) where they are mounted individually onto one side of a fine metal frame. A bond wire, a very fine wire, is then attached to the metal pattern on the top of the LED and the other end is attached to the other side of the frame.

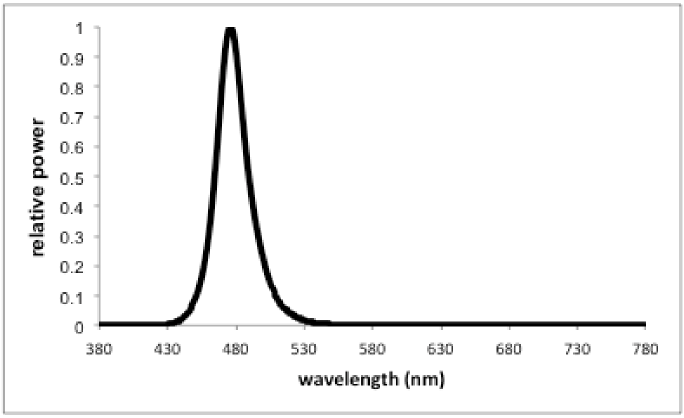
The frame is then moulded into a solid epoxy block to give the whole assembly strength and a final casting protects the die. The LEDs are then automatically tested and grouped before being packaged and sent to the warehouse.

3.1.6 LED Spectra

The light emitted by an LED is of a specific range of wavelengths and, therefore, colour. The spectrum of an LED depends on the dopant chemicals that were diffused into the die. The spectral range is quite narrow, resulting in a highly saturated colour. Phosphors can also be used within LEDs, allowing more spectral options for the emitted light.

Indium, gallium and nitrogen dopant chemicals produce LEDs that emit light in bands ranging from blue through to green. These are called InGaN LEDs after the chemical symbols for the dopants (In, Ga and N).

Indium, gallium, aluminium and phosphor dopants produce LEDs that emit light in bands ranging from green to red. These are often called InGaAlP LEDs after the chemical symbols for the dopants (In, Ga, Al, P).



Typical spectral curve of power versus wavelength for a specific LED

3.1.6.1 Multi-colour LEDs

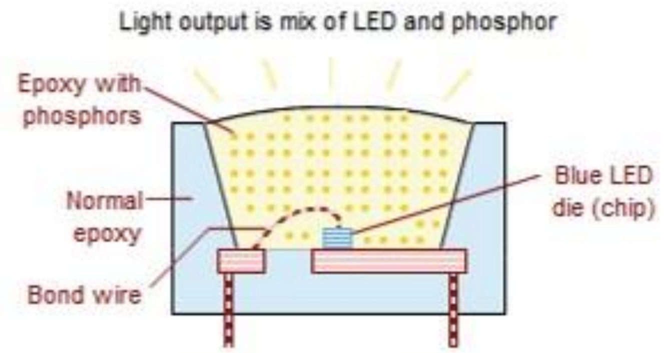
The light from individual LEDs, often a combination of red, green, blue (RGB) or red, green, blue, and yellow (RGBY), can be mixed together to produce white light. Manufacturers produce a number of LED packages that contain three or four die rather than one. These types of LEDs can be used for a variety of applications including large area video screens, media facades, and colour-tuneable architectural luminaires. Multi-colour LEDs pose some technical challenges. For instance, the light from the different coloured components must be thoroughly mixed before light is emitted; otherwise, coloured shadows can result. Often, the different coloured LEDs will change differently in response to temperature changes or over the course of their lifetimes. Therefore, RGB and RGY luminaires may experience colour shifts if the differing behaviour of the components is not considered.

3.1.6.2 Phosphor White LEDs

An LED die emits coloured light of a very narrow spectral region. The technique used to directly produce white light from a single LED die is similar to that used in fluorescent tubes. In a fluorescent tube, the excitation of mercury vapour produces ultraviolet radiation, which causes a phosphor coating mix on the inside of the glass tube to fluoresce and emit usable white light.

Structure of a single chip white LED:

- A phosphor is added to the top of the LED die (chip-level conversion) or a pool of phosphor is placed above the die (volumetric conversion, shown in the figure below).
- Blue light from the LED die stimulates the phosphor
- The phosphor emits a broadband yellowish light
- The light from the phosphor and the blue LED combine to produce white light of different correlated colour temperatures



White LED operation

Many different phosphors, that convert different wavelengths and emit different spectra, exist. Therefore, it is possible to create phosphor LEDs that emit a wide variety of spectral power distributions. At the present time, though, only a few broadly emitting phosphors are widely used in commercially-available LEDs.

3.1.6.3 Remote Phosphors

Since most phosphor white LEDs emit relatively little light in the long (red) wavelengths, their colour rendering can be unimpressive. To remedy this, it is currently common practice for LED luminaire manufacturers to include another element to add long wavelength power to the emitted light. Sometimes, this involves the use of red LED packages. Remote phosphors are also widely used. These phosphors convert some of the light incident upon them to longer wavelengths. Remote phosphors can be placed anywhere outside the LED die. The yellow-coloured optics (when the light is turned off) present on some LED luminaires and lamps are remote phosphors. Remote phosphors could be used to manipulate in the spectral output of an LED product in numerous ways, but at the present time, they are only widely used to increase the power of long-wavelength light.

3.1.7 Use of LEDs for Lighting

LEDs are very small light sources, which can be advantageous in the design of small compact light sources. The other key advantages are:

- Robustness
- Efficiency

Care should be taken when selecting LED lamps and luminaires; designers should ensure that appropriate measurement standards were used to determine photometric quantities.

Though individual LED dies emit light omni-directionally, in current practice most LEDs are mounted on pc boards and heat sinks, making the light emitted from them quite directional. Disappointment with LED products can arise when designers expect them to mimic older lighting technologies. Though some retrofit LED lamps emulate incandescent or fluorescent lamps successfully, many do not.

3.1.8 Reliability

In normal operation, the luminous flux from an LED gradually reduces over time. The decrease in luminous flux depends largely on the average operating junction temperature.

It can take many years of constant operation for the luminous flux of an LED to decline to a level where it is no longer usable. The most common method for specifying LED lifetime estimates the time after which the light output falls to 70% of its original value (L70). Even with this method, the lifetime for LEDs under the right conditions can be very long. In real applications, other components in LED luminaires, lamps, and light engines can have shorter lifetimes than the actual LEDs. For instance, an LED luminaire with a low-quality power supply, optics likely to darken over time, or non-durable mechanical casing may fail long before the LEDs reach end-of-life.

LEDs are robust and not made from fragile materials. They have a high tolerance to shock and vibration.

3.1.9 Product Performance - Choosing a Good LED

The selection of appropriate performance levels for LEDs can be complex and challenging, especially in light of the rapid improvements in technology that are being realised. The International Energy Agency's 4E SSL Annex has developed a number of "Product Performance Tiers" for LED lamps and luminaires. These are voluntary quality and performance tiers to address important product attributes such as:

- Efficacy
- Colour
- Lifetime

These product performance tiers are a limited number of proposed performance levels, agreed upon by IEA SSL Annex members that could be utilised by government, non-profit and donor agencies when designing programmes and policies. Tier 1 (guidance on minimum performance), and Tier 2 (high performance) are the most relevant for product specification. The objective is to provide a limited number of levels that can be utilised by programme designers to reduce costs of writing specifications and to facilitate economic advantages for industry/trade. Further, they help minimise compliance costs with SSL programmes and policies.

At the time of writing, performance tiers were available for the following types of LEDs:

- Non-directional Lamps
- Directional Lamps
- Downlight Luminaires
- Linear LED Lamps
- Outdoor Lighting (Street Lighting)
- High/Low Bay LED Luminaires
- Planar Luminaires

The latest version of the tiers can be found on the 4E SSL website: http://ssl.iea-4e.org

3.1.10 Product Labelling Schemes

In Australia, at the time of writing there was no energy labelling system in place for lamps or luminaires. However in the US, the ENERGY STAR® endorsement label is applied to products and appliances with superior energy efficiency within their category. It's a voluntary programme where industry partners identify and promote superior energy efficient products. The ENERGY STAR® logo can be seen in the figure below.

3.1.11 Other Resources

There are a number of other resources available related to LEDs, their performance and how to select an appropriate LED product. The Australian Government's LED Buyers' Guide is included in this manual as Appendix 5.

The Australian Government has also published a guide for lighting retailers, available from:
http://www.energyrating.gov.au/document/lighting-retailer-training-guide-0

3.2 Fluorescent Lamps

HEADS UP: Fluorescent Lamps and Energy Efficiency
Fluorescent lamps are typically very efficient in comparison to incandescent lamps, although LEDs can now surpass fluorescent lamps in terms of efficacy. Within fluorescent lamps there is also a range of efficiency and ballast choice also has a significant effect on efficacy – electronic ballasts allow the lamp to run more efficiently. When selecting fluorescent lamps for any use, the choice of colour temperature is critical to the quality of the lighting design.

Fluorescent lamps work by causing a phosphor coating in the inside of a glass tube to glow. Different types of phosphor give different coloured light. Although more expensive to buy, they are much cheaper to run and can last up to 15,000 hours. With careful design, they can replace incandescent and halogen lights in most situations.

Materials that give off visible light when exposed to other forms of radiation, such as ultraviolet or infrared, are described as being 'phosphorescent' or 'fluorescent'. Phosphorescent materials continue to glow after the exposing radiation is removed (such as the luminous paint used on wrist watches to make them visible in the dark). In contrast, fluorescent materials instantly cease to glow once the exposing radiation is removed (such as the powders used on the inside of TV screens).

The first fluorescent lamps were developed in 1940. These were straight tubes because the technology to make them in other forms was not available until the 1970s. Most fluorescent lamps in use today are still the straight tube type because they are relatively cheap and provide excellent light quality and economy of operation.

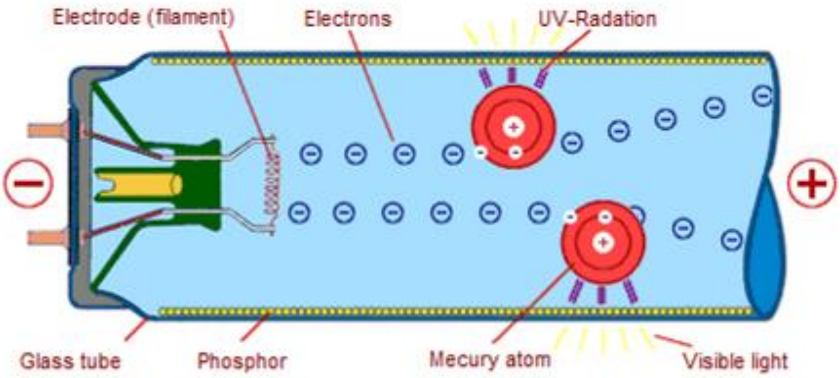
Because of their high luminous efficacy and long lamp life (compared with incandescent lamps), virtually all commercial and industrial lighting installations use fluorescent tubes. The technology continuously advances, with smaller diameter tubes, offering more light for longer and using less power.

The more recently introduced induction fluorescent lamps are special fluorescent lamps that work by inducing a current in the lamp from electrical coils around the outside of the tube. There are no electrical components inside the lamp, so no internal components to fail. In theory, an induction fluorescent lamp should never fail.

Performance summary (linear fluorescent tubes)	
Range	8 – 300 watt
Colour temperature	2,700 – 6,500 Kelvin
Life	800 – 16,000 hours
CRI	50 – 98
Efficacy	35 – 104 lm/watt

Pros	**Cons**
Economical to operate	Expensive to purchase
Large colour range	Sometimes requires ballast and starter
Cool operation	Slow to full brightness
Long life	Often unattractive
Soft light	Contains mercury

3.2.1 Fluorescent Lamps Components



Fluorescent lamp operating principle. See text for description.

Inside the glass tube of the lamp is an inert gas, either argon or a mixture of argon and krypton, at a pressure of only about 0.2% of atmospheric pressure. Also in the tube is a very small quantity of mercury between 3mg and 15mg depending on the size and type of the lamp. Mercury is a metal that is liquid at normal room temperature, but inside an operating lamp (which is hot), the mercury is in a vapour form, but its vapour pressure is extremely low in fact only about 0.0007% of atmospheric pressure. Fluorescent tubes (and CFLs) are technically referred to as 'low pressure gas discharge lamps'.

At the ends of the tube are electrodes - usually referred to as cathodes - which are electrically heated tungsten coils coated with barium oxide which when hot, have the property of releasing electrons.

3.2.2 Operation

When the lamp is started, the cathodes are first heated for a short time (1 to 2 seconds) in order to heat the cathodes so they release electrons. A high voltage is then applied across the two cathodes and a discharge is created as the gas and mercury vapour conducts the electrical current. The flow of electrons (i.e. the current), energises the vaporised mercury atoms to make them give off ultraviolet (UV) radiation. The inside of the glass tube is coated with a fluorescent powder, which is referred to as the 'phosphor'. The UV radiation makes the phosphor give off visible light but only whilst exposed to the UV (i.e. the process of fluorescence).

The discharge in the argon or argon/krypton gas causes the gas to give off a bluish glow, which can only be observed in a tube without the phosphor coating. This light constitutes only about 3% of the total light output from the lamp, the remaining 97% is generated by the phosphor.

3.2.2.1 Cold spot temperature

The efficiency of the fluorescence process is dependent upon the mercury vapour pressure, which in turn is governed by the temperature of the residual liquid mercury. Mercury vapour condenses back to the liquid form in the cooler parts of the tube. The lowest temperature region of the fluorescent lamp is called the 'cold-spot' and it's temperature is crucial in controlling how well the fluorescence process works.

The optimum mercury vapour pressure for the highest light output occurs when the cold-spot temperature is in the region of 40°C - 44°C. Fluorescent lamps are usually designed so that they achieve this cold-spot temperature when operating in an ambient temperature of about 25°C (i.e. typical room temperature).

3.2.3 Fluorescent Control gear

Fluorescent lamps are not designed to be operated directly from the mains supply. All fluorescent lamps require a device to generate a high voltage (more than 230V) to initiate the discharge and an additional device to control the discharge current. Unlike incandescent lamps, fluorescent lamps cannot control the current on their own and would draw such high currents from the mains that they would destroy themselves.

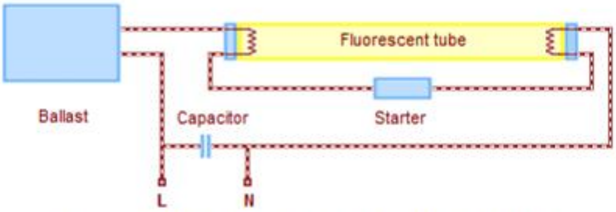
Control gear is essentially a device connected in series with a lamp to limit the current it draws down. Whether the control gear is electronic or non-electronic (conventional), it is necessary for the operation of discharge lamps, both fluorescent and high intensity discharge.

All discharge lamps have a negative current-voltage characteristic, which means that voltage decreases with increasing current and, unlike incandescent lamps, their electrical resistance decreases with increasing temperature. A discharge lamp without control gear would draw an ever increasing current as it runs up, and in the process destroy itself.

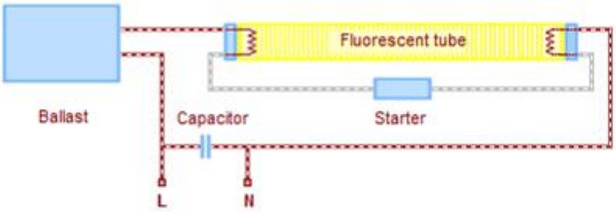
Transformers for operating low voltage incandescent lamps are also classed as control gear as they control the voltage and current to the lamp. Traditionally, transformers are big, heavy devices but they are being progressively replaced by more efficient, smaller lightweight electronic versions which are significantly more efficient.

3.2.3.1 Conventional Control Gear

It is first necessary to explain how conventional control gear (CCG) works as electronic versions work on similar principles but do so more efficiently.



A fluorescent tube with conventional control gear - starting the lamp



When the lamp is running the starter does not form part of the circuit

The key components in the circuit are:

- **Ballast (or choke)** - the device that controls the current through the lamp
- **Starter** - the switch that starts the lamp
- **Capacitor** - the component that corrects the power factor

3.2.3.2 Ballast

HEADS UP: Ballasts and Energy Efficiency

Electronic ballasts allow the lamp to run more efficiently and have significantly lower losses than wire-wound ballasts.

Ballast can also be referred to as a choke. It is a device for restricting (or 'choking') the current through the lamp. It is always connected in series with the lamp. In electrical terms, the ballast is a ‘self-inductance’ and consists of a coil of copper wire wound around a heavy iron core. As the alternating mains current passes through the coil, it generates an alternating magnetic field in the iron core. This alternating magnetic field induces a current in the coil opposing the mains current. The net effect is a limited current through the ballast and the lamp. The current limiting effect is very dependent upon the frequency of the supply current - the higher the frequency, the greater is the 'choking' effect.

Ballasts for use in the Australia are designed to operate at 230-240V and at the supply frequency of 50 Hz (cycles / second), which is the Australian mains supply frequency. The inherent resistance of the copper wire coil absorbs some of the power (given out as heat). Typically, the power absorbed by the ballast (known as 'ballast losses'), is about 25% of the rated power of the lamp being operated.

For example, the total circuit power of a 40W T12 fluorescent tube operated on CCG is about 50W. The lamp consumes 40W and the ballast absorbs 10W, which is 25% of the lamp power.

There are more efficient ballast known as ‘low-loss’ ballasts available. They are slightly more efficient in that they absorb less of the total circuit power compared with normal ballasts. This is achieved by a more complex design of the iron core and by using much thicker copper wire, which by having a lower electrical resistance, absorbs less power but makes ‘low-loss’ ballasts more expensive.

3.2.3.3 Starter

This is the switching device used to start fluorescent lamps. Essentially, it is a switch that first completes a circuit to heat up the lamp cathodes and then instantly breaks the circuit, which induces a very high voltage across the ballast and lamp. This high voltage starts the discharge in the lamp which then runs up to its normal operation. If the lamp fails to light first time, the starter automatically repeats the process until the lamp strikes. This is what causes a fluorescent tube to flash during start-up. Once the lamp is running, the starter no longer attempts to start the lamp.

The modern fluorescent starter is known as a 'glow' starter because it glows in operation and is designed to be an easily replaceable item.

St111Longlife | St151Longlife | St191Longlife | DEOS St191Safety | DEOS St173Safety | DEOS St172Safety

3.2.3.4 Capacitor

The current restricting effect of the ballast prevents the alternating mains current from being synchronous with the alternating mains voltage. The current is said to 'lag' behind the voltage and the magnitude of this 'lagging' is referred to as the 'power factor' of the circuit.

A capacitor has the opposite effect in that it makes the alternating current 'lead' the alternating supply voltage. By choice of suitable capacitor, connected across the L and N supply terminals, the 'lagging' effect of the ballast can be completely offset by the 'leading' effect of the capacitor. Such capacitors are referred to as 'power factor correction' capacitors (or PFC capacitors).Capacitors designed for power correction as part of fluorescent lamp control gear come in varying shapes and sizes. Many now have a plastic body.

The ideal power factor is 1. Without a PFC capacitor, the power factor is usually less than 0.5 in a fluorescent circuit. With a PFC capacitor, the power factor is restored to almost 1.

The fluorescent lamp circuit will operate normally without the PFC capacitor, but the power meter would register less than half of the apparent power being transmitted - a situation not encouraged by the electricity generation companies.

3.2.4 Starter-less circuits

'Switch start' circuits, as described above are the most commonly used CCG systems for fluorescent lamps.

There are other types of fluorescent circuits that employ only ballasts and transformers to operate the lamps. They need no power factor correction or starters - hence the name 'starter-less' circuits. These types of circuits are only seen in older light fittings and are not used in new installations.

3.2.4.1 Resonant start (RS) circuits

These circuits use two ballasts in series, one of which is connected to a capacitor to produce a high resonant voltage to start the lamp. The second ballast operates normally in controlling the lamp current.

Semi-resonant start (SRS) circuits

These circuits have a single ballast in series and a capacitor connected in parallel with the lamp. The voltage produced by this combination is sufficient to start the lamp and the ballast then operates normally to control the lamp current.

3.2.4.2 Instant start (IS) circuits

These circuits use part of the ballast windings to act as a preheat transformer to rapidly heat the lamp cathodes. The main part of the ballast is combined with a capacitor to produce a resonant high voltage to strike the lamp, which starts up very quickly, warranting the name 'instant start'. The ballast then operates normally to control the lamp current.

3.2.5 Fluorescent Phosphors

Phosphors are special photo-luminescent chemical compounds that produce visible light when exposed to other forms of radiation, such as UV radiation. Chemically, phosphors used in fluorescent lamps are derived from mixtures of halogenated phosphates of calcium, barium and strontium.

Phosphors used in 'basic' tubes are referred to as 'halophosphate'. The light these 'halophosphate' phosphors generate have high levels of blue and green but very little red. This bluish-green dominance results in poor colour rendering, and this disadvantage is typical of all 'basic' tubes.

3.2.5.1 Triphosphor fluorescent lamps

Triphosphor fluorescent lamps, tubes and CFLs, not only have the 'basic' halophosphate phosphor but also have three additional phosphors which give out peaks of light in the blue, green and red parts of the spectrum. Although these lamps actually have four phosphors, they are always referred to as 'triphosphor' lamps. Their advantage over 'basic' halophosphate lamps is that they reproduce colours of objects they illuminate very accurately i.e. they have very good colour rendering, with a colour rendering index of around 85.

3.2.5.2 De luxe phosphor lamps

Even better colour rendering is achieved with de luxe phosphor lamps, which have a colour rendering index from 93 to 98 and give light also as good as natural daylight. This is made possible by the addition of two extra phosphors to fill the spectral gap in the blue-green and orange-red parts of the spectral output where the triphosphors are slightly deficient. In fact, de luxe phosphor lamps have at least six different phosphors, and for this reason are also termed 'multi-phosphor' lamps.

These lamps are used almost exclusively for making critical colour comparison, such as colour matching of fabrics, paint mixing and colour printing. The application of so many phosphors on the inside of the glass tube has the disadvantage of absorbing and obscuring some of the light generated in the fluorescence process. As a result, de luxe phosphor lamps give out only about 70% of the light of their triphosphor equivalents, making them about 30% less luminous efficient.

3.2.5.3 Special phosphors

Red, green and blue coloured tubes contain only the phosphor that gives that particular colour - so there is minimal light loss and the colour is saturated. Because there is no suitable phosphor that produces a saturated yellow colour, yellow tubes have to be made from normal white triphosphor tubes that have a yellow coloured plastic coating on the outside of the tube. Coloured fluorescent lamps are used mostly for special colour effect displays in shops, pubs, bars and in the theatre.

For example, fluorescent tubes that have a higher emission in the red parts of the spectral output produce light that has a warmer touch and is ideal for meat and delicatessen displays (it makes meat look fresh!). Fluorescent tubes that have a higher red and blue component are used exclusively in horticultural applications for promoting the photosynthesis of plants in order to encourage their growth.

3.2.6 Colour Characteristics

Apart from light output (measured in lumens) of fluorescent lamps, the other two most important characteristics are 'colour appearance' (measured as colour temperature in Kelvin) and 'colour rendering' (measured in terms of colour rendering index).

3.2.6.1 Colour appearance

'Colour appearance' is how 'warm' or 'cold' a lamp's light appears. It is quantified by its colour temperature in Kelvin (the absolute temperature scale). The higher the temperature, the 'colder' the light appears. For example, Warm White which has more red and less blue is 3,000K, and daylight which has less red and more blue is 6,500K.

Quoting just a number to characterise a colour appearance is only of use to those who are familiar with the concept of colour temperature and the Kelvin scale. For triphosphor lamps, colour descriptions are used as well as the colour temperature because they are more easily remembered than numbers (see table). This helps guide users to the correct lamp for their particular application.

Colour description	Approximate colour temperature
Very warm white	2,700K
Warm white	3,000K
White	3,500K
Cool white	4,000K
Daylight	5,400K
Cool daylight	6,500K
Sky white	8,000K

3.2.6.2 Colour rendering index (CRI)

Also referred to as Ra, this is a numerical value up to 100 maximum (there is no minimum value). It indicates how good the light source is in rendering colours correctly (i.e. as they would appear in natural daylight).

The higher the number, the better the colour rendering. Natural daylight would give a CRI of 100.

Phosphor type	Colour rendering ability
Halophosphate (basic)	CRI 40 – 56 (fair)
Triphosphor	CRI 80 -89 (very good)
De luxe phosphor	CRI 90 – 100 (excellent)

Note: CRI values are not given to special coloured tubes and CFLs because the value could be negative and would be of no meaningful use.

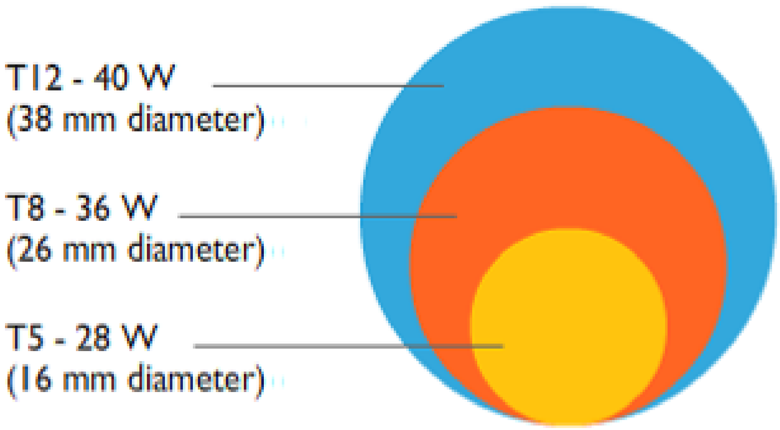
3.2.7 Types of fluorescent tubes

3.2.7.1 'T' Designation

Different types of fluorescent tubes are identified by their diameter and length (as well as their wattage). Although the European lamp manufacturers specify lamp dimensions in millimetres, the original (American) system of specifying diameter in the number of eighths of an inch and the length in feet, still persists in the lamp/electrical industry today.

T designation	Diameter (inches)	Diameter (mm)
T2	2 x 1/8" = 1/4"	7mm
T5	5 x 1/8" = 5/8"	16mm
T8	8 x 1/8" = 1"	26mm
T12	12 x 1/8" = 1½"	38mm

It is still common to refer to fluorescent tubes by their 'T' designation to specify the diameter - see table above and images below.




T2 (7mm)
Introduced in 1993


T5 (16mm)
Introduced in 1996


T8 (26mm)
Introduced in 1970


T12 (38mm)
Introduced in 1932

Because T8 and T12 tubes date back several decades, they still tend to be specified by their T designation and by their nominal length in imperial measurement (tube lengths are specified from end to end):

3.2.7.2 Bases

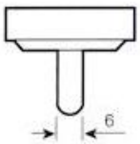
Because of their straight format, fluorescent tubes require electrical connections at both ends. Usually, each end of the tube has two pins so that each cathode can be electrically heated to facilitate starting the lamp. The exception is type 'X' tubes which are designed for use in explosive atmospheres and do not have cathode heating, and therefore have only one contact pin at each end.

Two pin fluorescent tube bases are all given the prefix 'G', followed by a number which is the separation of the pins, in mm. Single pin fluorescent tube bases are given the prefix 'Fa', followed by a number which is the diameter of the pin, in mm.

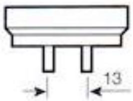
A T8 tube with the pin centres at 13mm apart. Has a G13 base.

A T12 'X' tube for use in explosive atmospheres. Has an Fa6 base.

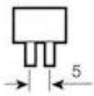
A 26mm diameter U shaped fluorescent lamp - designed for space saving luminaires. Has a 2G13 base.



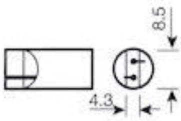
Base Fa6 Used in T12 'X' type tubes



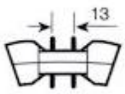
Base G13 Used in T8 and T12 type tubes



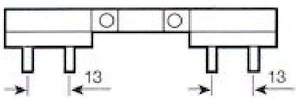
Base G5 Used in T5 (16mm) type tubes



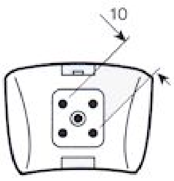
Base W4.3 Used in T2 (7mm) type tubes



Base 2GX13 Used in circular fluorescent lamps, 16mm tube diameter



Base 2G13 Used in U shaped fluorescent lamps, 26mm tube diameter



Base G10q Used in circular fluorescent lamps, 29-30mm tube diameter

3.2.7.3 Cold cathode fluorescent lamps

Cold cathode lamps are special fluorescent tubes that do not have heated cathodes. They have very long lifetimes, but are expensive and require special control gear to operate them. Their primary use is in decorative lighting and they have found many applications in the illumination of advertising displays.

3.2.7.4 Type X fluorescent tubes

Type X fluorescent tubes are characterised by having a single contact pin at each end of the tube. The design of the lamp is similar to T12 fluorescent tubes, but the single pin connection prevents the X type lamps from being used in normal 'cathode preheat' circuits.

These lamps are only for use in special fully enclosed light fittings that are used to provide illumination in dangerous explosive atmospheres such as encountered on gas and oil rigs. The fact that the cathodes have no means of being electrically heated means that they pose no risk of being a source of ignition in an explosive atmosphere (should the light fitting be accidentally broken open, breaking the tubes and exposing the lamps’ cathodes to potentially explosive gases).

3.2.7.5 Induction fluorescent tubes

Induction fluorescent lamps operate on the principle of induction. Unlike incandescent or conventional fluorescent lamps, they have no electrical connection going inside the glass bulb; the energy needed to generate light is transferred *through* the glass envelope solely by electromagnetic induction. Typically they are a closed rectangular tube, 54mm in diameter, with a triphosphor coating. It employs amalgam technology because their high wattages (up to 150W) generate high operating temperatures.

Operation

Coils of wire around the short sides of the lamp carry a high frequency current (supplied by specialist electronic control gear). The magnetic field generated by these coils induces a current to flow through the gas around the inside of the closed tube. The current excites the mercury in the amalgam to emit ultraviolet which then causes the phosphor to fluoresce, in the same way as a normal fluorescent tube.

The luminous efficacy is around 80 lm/W - not quite as high as the T5 & T8 triphosphor tubes. However, the outstanding advantage of induction fluorescent tubes is that with no internal cathodes to fail, they will theoretically never fail. Their useful life is stated as 60,000 – 100,000 hours (more than 10 years continual use) and this is based on a lumen maintenance of 70%.

Uses

Induction fluorescent tubes are a truly 'fit and forget' light source - ideal for installations where accessibility for maintenance is difficult and costly, such as factories and road/rail tunnels. Lamps are available in 75W, 100W and 150W ratings. However, they can only be operated with specialist electronic control gear.

3.2.8 Characteristics of Tubes

3.2.8.1 T12 (38mm diameter) tubes

This is the original design from the 1930s, but in spite of being old technology, is still in use today, although the demand is declining in favour of more efficient T8 and T5 tubes. With a few exceptions, T12 tubes are 'basic' tubes using halophosphate phosphors. They are not recommended for applications where good quality lighting is required or where energy saving lighting is specified. Their use is restricted to industrial and amenity lighting where good colour rendering is not of paramount importance.

T12 Fluorescent tubes	
Sizes	Starts at 2ft (20W) and goes up to 6 ft (80W)
Efficacy:	Luminous efficacy is in the range of 61 to 86 lm/W

New installations rarely use T12 tubes. Modern T8 and T5 fluorescent tubes offer greater energy savings, as well as superior light output and quality. The only exception is when 8ft tubes are required.

3.2.8.2 T8 (26mm diameter) tubes

These tubes were introduced in the 1970s in the halophosphate version. T8 fluorescent tubes are designed to replace similar wattage T12 tubes as they come in the same lengths and have the same G13 base connections. The only exception is the 8 ft T12 tubes for which there are no T8 equivalents. The maximum practical length for T8 (1 inch) diameter glass tube is 6 ft. as a 1 inch diameter glass tube in an 8 ft. length would be too 'bendy' and too easily broken during insertion or removal.

T8 Fluorescent tubes	
Phosphors and sizes	Halophosphate phosphor (‘basic’) lamps from 18" (15W) to 6 ft (70W), CRI 50 - 60 Triphosphor phosphor lamps from 19" (10W) to 6 ft (70W), CRI 85. Multi-phosphor lamps from 18" (15W) to 5 ft (58W), CRI 93 - 98)
Efficacy	Halophosphate and multi-phosphor T8 fluorescent tubes have similar luminous efficacy to their T12 equivalents. Triphosphor T8 tubes are 10-15% more luminous efficient, even when operated on conventional control gear. If operated on modern high frequency control gear, the improvement in luminous efficacy is then as high as 30%.

T8 triphosphor tubes are actively promoted as energy saving alternatives to T12 tubes. For example, by replacing a 40W (4 ft.) T12 tube with a 36W (4 ft.) T8 tube, the energy saved is 4W (i.e. 10%) and the light output from the triphosphor tube is also 10% more.

3.2.8.3 T5 (16mm diameter) tubes

T5 fluorescent tubes can be divided into two technologies - 'old' and 'new'.

Old technology: These first appeared in the early 1970s. They generally use halophosphate phosphors and have relatively low luminous efficacies (40 to 66 lm/W). Because of their small size and low wattage - ranging from 4W (6") to 13W (21"), they have restricted use. Their application is in small illuminated road signs, battery powered emergency lighting and domestically in under cupboard kitchen lighting.

New technology: The 'new' technology T5 fluorescent tubes were first introduced to the market (in Europe) in 1996. These tubes represent the latest developments in triphosphor fluorescent tube technology. They are currently the most luminous efficient of all fluorescent lamps. They are specifically designed to be operated only with high frequency electronic control gear, making 'new' T5 lighting systems the most energy efficient currently available.

They are not interchangeable with either T8 or T12 tubes. They have different pin base connections to T8 and T12, and are approximately 2" shorter than the standard imperial lengths. 'New' T5 tubes are for use only in dedicated light fittings that have specially designed reflectors that take advantage of the narrower light source. Smaller light sources produce less obscuration of the reflected light, allowing more of the light generated by the lamp to come out of the fitting.

T5 Fluorescent tubes	
Variations available	HE (HE = High Efficacy) Wattages: 14W, 21W, 28W and 35W Lengths: 549 mm (21W) to 1449 mm (35W) Use: HE tubes are used where the most energy efficient system is required. HO (HO = High Output) Same lengths as HE but in larger wattages for higher light output. Wattages: 24W, 39W, 49W, 54W, 80W Lengths: 549 mm (24W) to 1449 mm (80W) Use: HO tubes are used where the requirement for high light levels is more important than energy efficiency. FC (C = Circular) Essentially HO tubes in circular format. Wattages: 22W , 40W and 55W Overall diameter: 225 mm (22W) and 300 mm (40W & 55W) Use: FC circular tubes are used in applications where more attractive, aesthetically designed light fittings are preferred to the conventional long narrow types
Efficacy	The HE version is highly efficient at 104 lm/W. About 20% more luminous efficient than T8 triphosphor tubes. HO and FC versions have slightly lower luminous efficiency than HE
Colour	'New' T5 tubes are available in triphosphor with HO also available in Deluxe triphosphor. They are available in all the colour appearances - from Very Warm White at 2,700K to Sky White at 8,000K.

The advantage of using 'new' T5 lighting systems is that the light fittings are much smaller and compact. Also, because the fitting efficiency is higher, less are required (than T8 fittings) to provide the required illumination levels. This is a significant factor in keeping the installation and operating energy costs as low as possible, without sacrificing the level or quality of the light.

3.2.8.4 T2 (7mm diameter) tubes

These 'pencil slim' fluorescent tubes are only 1/4" (7 mm) in diameter. They have a unique base connection (referred to as W4.3) used only for this T2 tube. It needs special electronic control gear for its operation.

T2 Fluorescent tubes	
Sizes	Available in 4 sizes: 219mm(6W), 321mm(8W), 423mm(11W) and 524mm(13W)
Colour	Colour appearances in Warm White (3,000K), Cool White (4,000K) and Daylight (6,000K). All offer good colour rendering with CRI 70 - 79

FM (T2) tubes are not designed for general lighting as their wattages and hence their light outputs are too low. However, because of their very small diameter they are used extensively in display cabinets, for illuminating signs, picture lighting or any application where unobtrusive lighting is required.

3.2.9 Lamp Performance

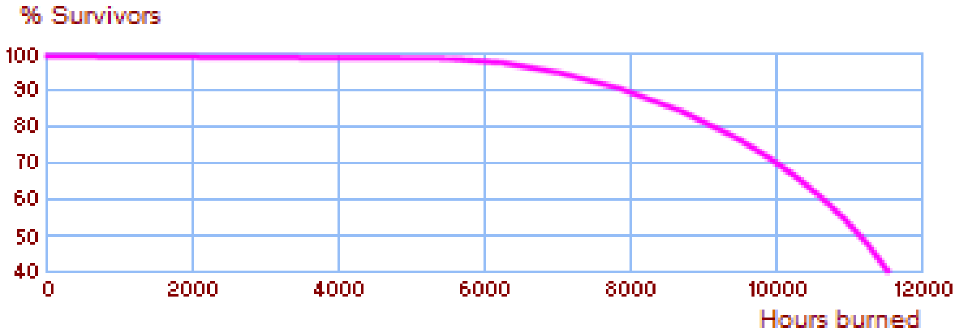
For fluorescent tubes (and CFLs), the most important aspects of their performance are the following:

- Efficacy
- **Lifetime** - the average operating hours
- **Lumen maintenance** - how the light output changes over the lifetime of the lamp
- **Frequent switching** - how the life is reduced from the effect of being switched on and off
- **Ambient temperature** - how the ambient temperature around the lamp affects its light output

3.2.9.1 Lifetime

The industry states that fluorescent lamps will last for a 'rated average life', which is the time, in hours, when 50% of the lamps in a test batch would be expected to have failed. This is the same as saying when 50% are still surviving and is defined as the “mortality” rate of the lamp.

Manufacturers state a figure for 'rated average life' in their literature, such as 10,000 hours or 15,000 hours; but for the lighting designer and even the end user, it is important to know the rate at which lamps in an installation will fail so that the annual lamp replacement cost can be estimated. For this reason, the life performance of fluorescent lamps is expressed in the form of a 'survivor graph', which shows the percentage of surviving lamps relative to the cumulative burning hours. The time at which 50% of the lamps are still operating (i.e. when 50% have failed) is what is stated as the 'rated average life'.



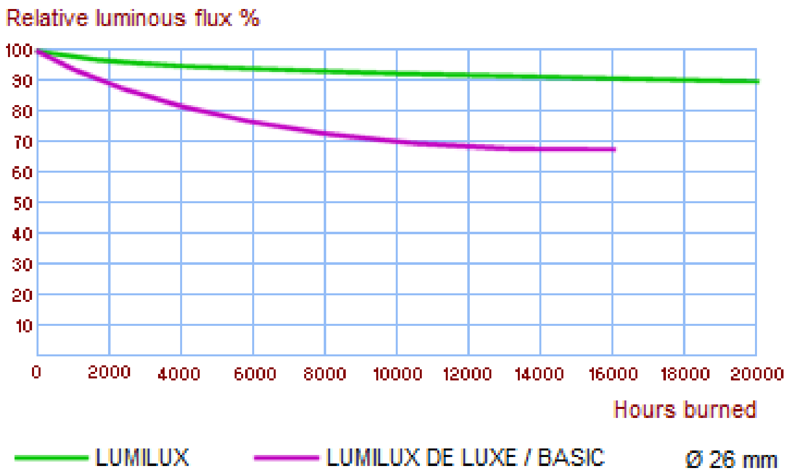
Survivors: Standard 26mm (T8) Fluorescent tubes (Conventional Control Gear)

3.2.9.2 Lumen maintenance

Knowing the rate at which the light output from a fluorescent lamp declines during its lifetime is quoted as 'lumen maintenance'. It is important in designing light schemes to be sure there is always enough illumination for the particular tasks being undertaken. Too much light can be uncomfortable, but not enough light can be stressful and potentially dangerous.

Lumen maintenance is always shown graphically, otherwise it would require a long list of lumen levels at different operating hours.

Triphosphor fluorescent tubes (T8 & T5 FH/HO/FC) all have excellent lumen maintenance, losing only about 10% of their initial output over their lifetime. Triphosphor CFLs perform less well, with about a 20% light loss over their lifetime. 'Basic' halophosphate tubes tend to suffer the largest light loss, with about 30% loss over their generally shorter lifetime.



Lumen Maintenance graph for OSRAM T8 Fluorescent tubes

3.2.9.3 Frequent switching

All fluorescent lamps (with the exception of certain specialist lamps), suffer from reduced life if subjected to abnormally frequent on / off switching. This is because the high starting voltage gradually erodes the cathodes, which fail sooner if the lamp is given frequent starts. The effect is more pronounced with lamps operated from conventional (magnetic) control gear. With electronic control gear the effect is less severe, but there can be still a reduction in lamp life.
The life reduction varies according to how frequently the lamp is switched. Life claims for fluorescent lamps are based on life testing with one switch cycle every 3 hrs (i.e. 2¾ hrs /¼ hr OFF). This equates to about 3 switching cycles in an average working day. More frequent switching can result in reduced lamp life.

This effect is very important to be aware of, especially with installations using presence detectors, where switch frequencies could be several hundred times a day. Under such conditions, the cost of having to frequently replace lamps would considerably outweigh any savings in energy costs by installing presence detectors.

3.2.9.4 Ambient temperature

The ambient temperature of the atmosphere surrounding an operating fluorescent lamp can significantly affect its luminous output. Both very low and very high ambient temperatures result in reduced light output - although amalgam technology has improved the high and low temperature performance.

For 'new' T5 FC , T8 and T12 tubes, the peak light output is achieved at an ambient temperature around 25°C. For 'new' T5 tubes, the peak light output is achieved at an ambient temperature of around 35°C.

CFLs are sensitive to ambient temperature as well as their operating position. Mercury only CFLs give their peak light output in the 20° - 25°C region, with the lamp in either base up or horizontal position. In the base down orientation, the peak light output occurs at a much lower ambient temperature of 5° - 10°C. This is the recommended burning position for the CFL used outdoors, where the ambient temperature is lower, especially in winter.

Amalgam lamps have the advantage of maintaining more than 90% of the peak light output in an ambient temperature range of around 5° - 70°C.

3.2.10 Marking of Fluorescent Lamps[2]

Fluorescent lamps are identified by a standardised code that reveals valuable information about operating characteristics and physical dimensions. Manufacturers' codes, found on the lamps and in catalogues, may vary slightly from the generic designations. However all major lamp manufacturers base their codes closely on the identification system discussed below.

The coding system provides the user with the three essential parameters of the tube: Lamp power (wattage), colour rendering (CRI value) and colour temperature (K). Some examples are shown below:

Rapid-start (40 watts or less) and preheat lamps

Rapid-start lamps are the most popular fluorescent lamp type used in commercial applications such as office buildings.

F30T12/CW/RS	
F	Fluorescent
30	Rated nominal wattage
T	Shape - this lamp is shaped like a tube
12	Diameter in eighths of an inch; this lamp is 12/8 (1.5) inches in diameter
CW	Colour; this lamp is a cool white lamp
RS	Mode of starting; the lamp is a rapid-start lamp Preheat lamps do not have "RS" as a suffix

Note: Some lamps may be designated F40T12/ES, but the lamp draws 34 instead of 40 watts; the ‘ES,’ a modifier which stands for ‘energy-saving,’ indicates this. ES is a generic designation; actual manufacturer designations may be ‘SS’ for Supersaver, ‘EW’ for Econ-o-Watt, ‘WM’ for Watt-Miser and others.

After the mode of starting, another number may be added to indicate colour rendering and colour temperature if the lamp's colour (CW, WW, WWX, etc.) is not indicated. The number will often be three digits, the first indicating colour rendering (a ‘7’ standing for ‘75,’ for example) and then the next two indicating colour temperature (a ‘41’ standing for ‘4,100K,’ for example).

High-output rapid-start lamps

F48T12/WW/HO	
F	Fluorescent
48	Rated nominal wattage
T	Shape - *this lamp is shaped like a tube*
12	Diameter in eighths of an inch; this lamp is 12/8 (1.5) inches in diameter
WW	Colour - *this lamp is a warm white lamp*
HO	High output lamp operating on 800mA current

Very high-output rapid-start lamps

F72T12/CW/VHO	
F	Fluorescent
72	Nominal length of the lamp in inches
T	Shape - *this lamp is shaped like a tube*
12	Diameter in eighths of an inch; this lamp is 12/8 (1.5) inches in diameter
CW	Colour - *this lamp is a cool white lamp*
VHO	Very high output lamp operating on 1500mA current

Note: Instead of VHO, lamps may use brand names such as ‘1500’ or ‘PowerGroove’

Instant-start lamps

F96T12/WWX	
F	Fluorescent
96	Nominal length of the lamp in inches
T	Shape - *this lamp is shaped like a tube*
12	Diameter in eighths of an inch; this lamp is 12/8 (1.5) inches in diameter
WWX	Colour - *this lamp is a deluxe warm white lamp*

Other fluorescent lamps

- ‘FC’ instead of ‘F’ means the lamp is circular.
- ‘FB’ or ‘FU’ instead of ‘F’ means the lamp is bent or U-shaped. The suffix ‘U’ may also be followed by a ‘/’ and a number that indicates the distance between the lamp's legs in inches
- ‘FT’ instead of ‘F’ is used for twin-tube T5 lamps

3.3 Compact fluorescent lamps

HEADS UP: Compact Fluorescent Lamps and Energy Efficiency

Compact fluorescent lamps (CFLs) represent a very efficient choice for residential applications and where linear fluorescent tubes are not suitable, although LEDs can now surpass CFLs in terms of efficacy. CFL quality has improved significantly in recent years and they have become popular in almost all Australian households. Once again, choice of colour temperature is critical to good lighting design.

Compact fluorescent lamps (CFLs) have all the benefits of fluorescent tubes but take advantage of the fact that fluorescent lamps will operate just as well even if the tube is bent double (or even treble). The electrical discharge follows the bore of the tube irrespective of its contour. This allows for all the electrical connections to be at one end of the lamp and they can be designed to fit into conventional bayonet or screw fitting light sockets, greatly extending the scope of CFL applications as a more energy efficient replacement for incandescent lamps in many light fittings.

The operation and performance characteristics modes of CFLs, are the same as for fluorescent lamps, as covered in the previous section.

Performance summary	
Range	Compact fluorescent integrated: 6 – 42 watt Compact fluorescent non-integrated: 5 – 55 watt
Colour temperature	Compact fluorescent integrated: 2,700 – 6,500 Kelvin Compact fluorescent non-integrated: 2,700 – 6,500 Kelvin

Life	800 – 16000 hours
CRI	Compact fluorescent integrated: 76 – 82 Compact fluorescent non-integrated: 80 – 92
Efficacy	Compact fluorescent integrated: 33 – 65 lm/watt Compact fluorescent non-integrated: 46 – 82 lm/watt

Pros	**Cons**
Economical to operate	Expensive to purchase
Large colour range	Sometimes requires ballast and starter
Cool operation	Slow to full brightness
Long life	Often unattractive
Soft light	

A new standard will be introduced for CFLs sold in Australia from November 2009. This standard will specify requirements for a range of efficiency and quality issues including lifetime requirements.

3.3.1 Types of CFLs

There are two types of CFLs:

- ***Pin-based CFLs*** - with pin base connections for operation from control gear that is separate from the lamp

- ***Integral ballast CFLs*** - where the control gear is an integral part of the lamp and housed in the base of the CFL

3.3.1.1 Pin based CFLs

Pin-based CFLs have connections for operation from control gear that is separate from the lamp, i.e. the control gear is NOT housed within the lamp. They have bases with either 2 pins or 4 pins for making the electrical connections to the lamp. Pin-based CFLs cover a very large range of wattages from 5W to 120W increasing in size with increasing wattages.

CFLs with 2 pin bases are for operation only from conventional magnetic ballasts. The starter switch for striking the lamp is contained inside the base of the lamp. This circuit arrangement only needs two electrical connections to the lamp - hence the 2 pins. These CFLs will not operate from electronic control gear.

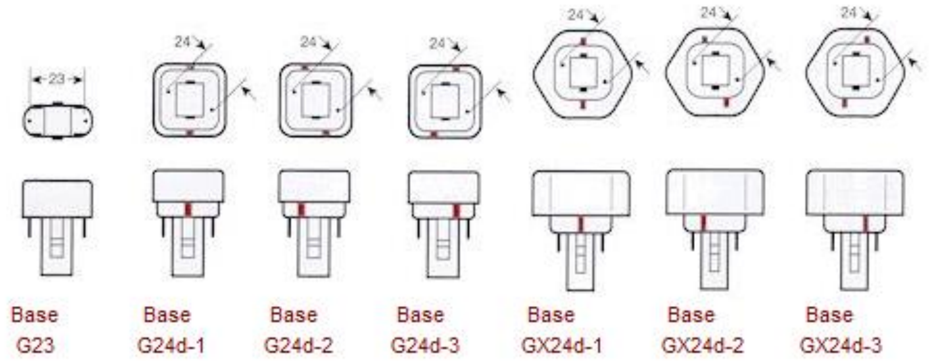
CFLs with 4 pin bases are usually for use only with electronic control gear (ECG). They do not have integral starter switches as the starting circuit is part of the separate electronic control gear. Both cathodes in the lamp each require 2 connections for their electrical heating during starting - hence 4 pins in total.

Pin bases

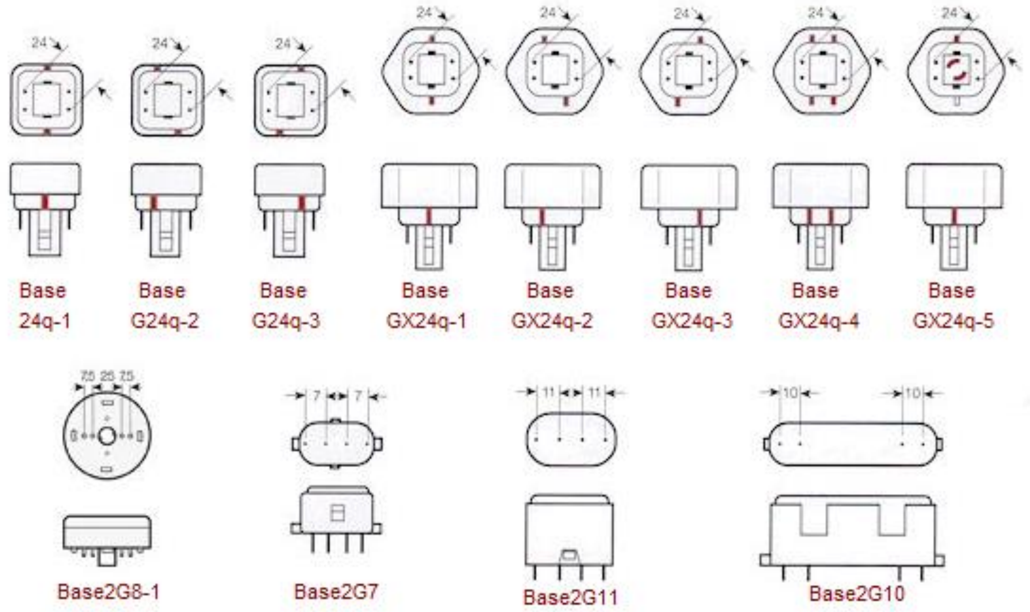
There are a variety of styles of CFL bases. Within each style there can be several variations that superficially all look the same, but in fact they are all slightly different from each other. Although they have the same pin positions, each base has two small flanges, the position of which is unique to that wattage of lamp. The flanges line up with corresponding slots in the lamp holder, preventing the CFL being put into the wrong light fitting where it would be operated incorrectly, causing possible damage to both lamp and control gear.

The following diagrams show some of the base variations and refer to the manufacturers' lighting catalogues to see which lamp has which base.

2 pin bases:



4 pin bases:



3.3.1.2 Integral Ballast CFLs

CFLs with the control gear (usually electronic) built into the lamp base are generally referred to as 'integral ballast' CFLs - sometimes written in abbreviated form as CFLi. These CFLs are the well known 'energy saving lamps' used extensively in the home. They are fitted with normal Edison screw bases to enable them to be directly inserted into normal domestic lamp-holders. They can provide up to 80% energy saving over normal incandescent lamps (more details below).

The very first 'integral ballast' CFLs used magnetic control gear and appeared on the market in 1979. These lamps were big and heavy, but were superseded by the more compact lightweight versions using electronic control gear in 1984.

Most integral ballast CFLs sold in Europe use a triphosphor (2,700K) to produce a warm effect lighting with very good colour rendering - similar to the conventional lamps they are designed to replace.

Lamps are also manufactured with Cool White and Daylight triphosphors, but these are not popular in the Northern Hemisphere as the colour appearance is too 'cold'. However, they are more popular in tropical countries where a 'cold' effect light is preferred.

Since their introduction in the mid 1980s, integral ballast CFLs have continually improved. Not only has the range and variety increased, but they have become much smaller, with their life virtually doubling - from 8000 hours in 1984 to 15000 hours today. Integral ballast CFLs range from 3W (single turn) to 30W (quadruple turn).

Until the mid 1990s, these 'integral ballast' CFLs were all of the parallel tube design (and are sometimes called 'stick' lamps). The public preference has always been for CFLs to be the same size and shape as conventional incandescent lamps, but it was not until 1995 that the technology was able to produce energy saving lamps that looked like normal incandescent lamps. They are available in a range of wattages to replace conventional incandescent lamps and candle lamps.

“Double-envelope” CFLs are in essence the same as the tubular types but with an outer glass or plastic bulb to give them the familiar shape of conventional incandescent lamps.

Because of the enclosed design, the operating temperatures of the fluorescent tubes inside the outer bulb are much higher than normal, so these lamps use amalgam technology to maximise the light output.

Special integral ballast CFLs

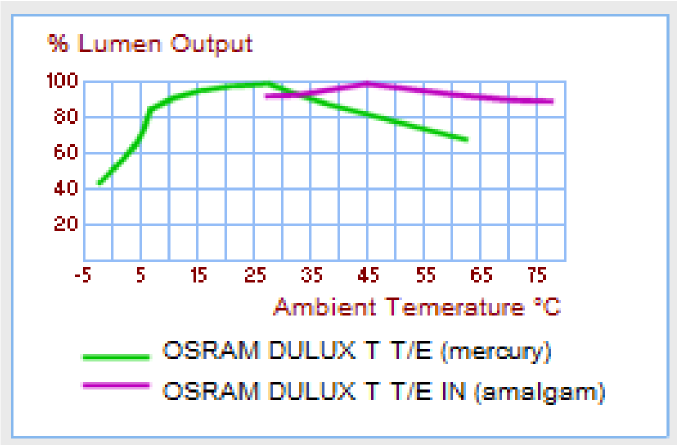
Manufacturers have also developed some special 'integral ballast' CFLs with unique features for particular applications:

- Integral ballast CFLs with special electronic control gear that allows them to have a high and a low light output - controlled by the mains switch. This switch dimming feature is suited to mood lighting in living rooms or for low level night time lighting on stairs, landings or children's bedrooms.
- Integral ballast CFLs have infinitely variable light output, and as such can be introduced into all applications in combination with adequate phase control dimmers.
- Energy saving integral ballast CFLs that can provide automatic outdoor security lighting via a light sensor built into the base. They automatically switch on at dusk and off at dawn, without the need for a time switch.
- Integral ballast CFLs with special electronic control gear, gives the lamp a preheat 'boost' start so that it provides a high light output much quicker than other CFLs and prolongs the life of the cathodes. These lamps are ideal for installations that are frequently switched, e.g. for use on frequently operated timed switches in corridors, entrances and stairwells in multi-occupancy dwellings, as they can be switched on and off any number of times without reducing the lifetime of the lamp.
- Integral ballast CFLs enclosed in a large-bulb lamp. They are designed for use in luminaires where the lamp is visible. The outer bulb is made of plastic, which helps reduce weight and improve impact resistance.
- Integral ballast CFLs designed to replace conventional incandescent reflector lamps (e.g. R80, R95 or PAR 38). These can greatly reduce the thermal load on the objects they illuminate.

3.3.2 Amalgam Technology

When fluorescent lamps operate in conditions where the temperature of the lamp is much higher than normal, the fluorescence process becomes less efficient, making the lamp lose light output. This happens because the high operating temperature increases the mercury vapour pressure in the lamp and this results in reduced UV for the fluorescence process. This is very apparent where CFLs (especially the higher wattage versions that give out more heat) are operated in compact, often enclosed, fittings in interior installations.

The following graph shows how lumen output is affected by ambient temperature for both mercury and amalgam CFLs.



The light output loss problem is most pronounced with interior lighting installations where room temperatures are generally high, especially at ceiling level. For this reason the industry has developed 'amalgam CFLs'.

Amalgam lamps use a low mercury content alloy (the amalgam), often in pellet form, to stabilise the mercury vapour pressure inside the lamp. This keeps the lamp efficacy high over a wider range of ambient temperatures and virtually eliminates the fluctuations of light output at varying temperatures. In addition, amalgam technology allows a reduction in the amount of mercury used in fluorescent lamps.

The disadvantage of amalgam technology is that there is a noticeable ‘warm-up time’ when the lamps are switched on.

3.3.3 Marking of Compact Fluorescent Lamps

Compact Fluorescent lamps are either pin-based (they plug into a socket) or they are medium screw-based (they screw into the same socket as common incandescent lamps). The following describes the National Electrical Manufacturers Association (NEMA) generic designation system for pin-based compact fluorescent lamps. The NEMA generic designation system for pin-based compact fluorescent lamps consists of four parts:

CF + shape + wattage / abbreviated base designation

- The prefix ‘CF’ is used for all types of compact fluorescent lamps that comply with the American National Standards Institute (ANSI) definition of a self-supporting lamp with a single base.
- The ‘shape’ designator is chosen from the following:
    - T - twin parallel tubes
    - Q - four tubes in a quad formation
    - TR - triple tube (including three twin tubes in a delta formation or three tubes in an arch). This is new shape designator to address the increased use of this lamp type. Some publications may refer to triple tube using their former 'M' designator

  - S - square shaped
  - M - a combination of tubes (multiple) not covered by any of the above shape designators
- The ‘wattage’ is the nominal wattage, followed by ‘W’.
- The ‘abbreviated base designation’ after the ‘/’ separator, is the ANSI/IEC (International Electrotechnical Commission) designation which includes the number of pins, but excludes any keyway information. The base designation, which can be determined from lamp catalogues, is essential to differentiate between lamps of the same wattage, but which have different pin configurations (as described in the section on CFLs).
- Additional information, such as colour, may be added after a further ‘/’ separator.

For example:

Identification mark	Description
CFT9W/G23	9 watt twin tube with G23 base
CFQ26W/ G24d	26 watt quad tube with 2 pin G24 base
CFQ26W/G24q	26 watt quad tube with 4 pin G24 base
CFTR32W/G24q/835	32 watt triple tube with 4 pin G24 base, >80CRI, 3,500K

3.4 High Intensity Discharge Lamps

HEADS UP: High Intensity Discharge Lamps and Energy Efficiency

High intensity discharge (HID) lamps are usually very efficient. The exception is high pressure mercury (or ‘mercury vapour’) lamps which are being phased out in various parts of the world due to their poor efficiency and high mercury content. LED lighting is now becoming a more efficient alternative in many applications.

Electronic control gear for HID lamps will also reduce energy consumption and should be selected where feasible.

High-intensity discharge (HID) lamps are a type of electrical lamp that produces light by means of an electric arc between tungsten electrodes housed inside a translucent or transparent fused quartz or fused alumina arc tube. This tube is filled with both gas and metal salts. The gas facilitates the arc's initial strike. Once the arc is started, it heats and evaporates the metal salts forming a plasma, which greatly increases the intensity of light produced by the arc and reduces its power consumption. This is the same principle as lightning where the high voltage that builds up in the storm clouds discharges itself through to the ground. The passage of electrical current through the atmosphere (mainly nitrogen) 'excites' the nitrogen atoms to give out a bluish-white light during that split second of the discharge.

High intensity discharge lamps produce a range of visible radiation at specific wavelengths consistent with the metal used in the lamp. Typical metals are mercury, sodium and a combination of metal halides, which effect their colour appearance and colour rendering properties. Mercury and sodium lamps have their characteristic colours and are not renowned for their good colour rendition. They tend to be used where good colour rendering is not the main requirement. Metal halide lamps produce ‘daylight’ quality white light with extremely good colour rendering and so are used in applications where accurate colour reproduction is paramount.

Compared with fluorescent and incandescent lamps, HID lamps have higher luminous efficacy since a greater proportion (about 25%) of their radiation is in visible light as opposed to heat. Their overall luminous efficacy is also much higher as they give a greater amount of light output per watt of electricity input.

During the 1930s when fluorescent tubes were being developed, scientists also looked into ways of making sodium and mercury generate visible light. By the mid 1930s, the first commercial high pressure mercury and low pressure sodium lamps became available. Almost 30 years later, the high pressure sodium lamp was developed and about the same time the first metal halide discharge lamps appeared. There is also a type of discharge lamp that does not use metals to generate the light but relies on the excitation of xenon gas.

The name high intensity discharge lamp has been adopted because all these discharge lamps produce light from a relatively small intense electrical discharge (i.e. compared with the larger discharge in a fluorescent tube). The table below summarises the key properties of the different types of HID lamps.

Lamp type	Range (watts)	Colour temperature (Kelvin)	Life (Hours)	CRI	Efficacy (lm/W)
High pressure mercury	50 – 1,000	3,000 – 4,000	15,000 - 24,000	40 – 60	32 – 60
Low pressure sodium	18 - 180	Below 2,000	16,000	15	100 – 200
High pressure sodium	70 – 1,000	1,900 – 2,100	12,000 - 32,000	23 – 25	70 – 120
Metal halide	50 – 2,000	3,000 – 6,000	6,000 - 24,000	60 – 90+	65 – 120
Xenon discharge		6,000 – 6,500		>90	

Pros	Cons
Usually very economical to operate	Expensive to install and re-lamp
Long to extremely long life (up to 32,000 hours)	Control gear required for operation
Metal halide lamps give good colour rendition	Sodium lamps give poor colour rendition
	May require the use of safety screens
	Time delay before full light output & re-strike
	Not suitable for dimming

3.4.1 Performance of HID Lamps

Unlike fluorescent lamps, HID lamps are not adversely affected by either high or low ambient temperatures. In fact, high pressure sodium and metal halide lamps are frequently used to provide the permanent lighting in cold storage areas. Obviously, excessively high ambient temperatures will have a damaging effect by causing the lamps to overheat and fail prematurely.

The essential factors for the performance of HID lamps are:

- **Life** - how long do they last
- **Lumen maintenance** - how does the light output decline over operating hours
- **Luminous efficacy** - how much light is produced for the energy consumed

Like fluorescent lamps, the claimed 'rated average life' represents the operating time (in hours) to a 50% survival level (which is the same as a 50% failure level) for a large group of lamps on a pre-determined switching cycle (hours on and hours off). Survival levels and lumen depreciation of operating time are usually expressed graphically.

3.4.2 How HID Lamps Work

Apart from xenon discharge lamps, all HID lamps operate on the principle of light being generated from the excitation of atoms of certain metals in an electrical discharge between two electrodes, through inert gases such as neon, argon and xenon.

The bright discharge between the electrodes is not straight, but curved into an arc shape. This is due to the intense convection movement of the hot gas in the discharge tube.

3.4.2.1 Control Gear

As with fluorescent lamps, High Intensity Discharge lamps are not designed to be operated directly from the mains supply, but require control gear for their ignition and operation. HWL high pressure mercury lamps with their integral filament are the only exception.

It is usual to house the control gear in the light fitting. Sometimes, depending on the aesthetic requirements for the lighting system, the control gear is sited remotely and connected by cable to the light fitting. The remote location of the control gear requires specially designed ignitors and cabling in some cases to ensure an adequate starting voltage at the lamp.

3.4.2.2 Ballast

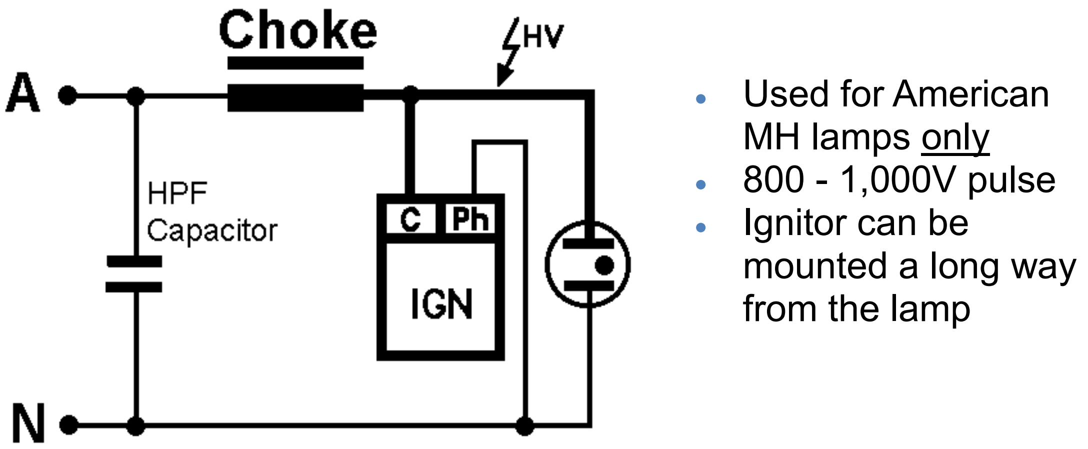
As with the fluorescent lamp operation, the ballast in an HID circuit can also be referred to as a choke and is defined as a current limiting device.

3.4.2.3 Ignitor

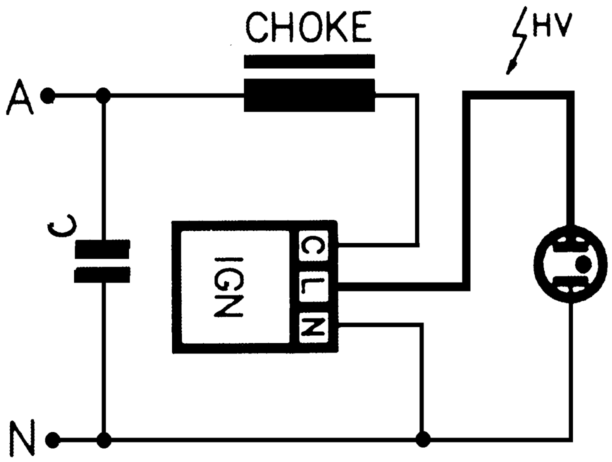
Switching devices for fluorescent lamps are always referred to as 'starters'. For high intensity discharge lamps such as high pressure sodium and metal halide, the internal gas pressure is much higher and requires a much higher voltage to strike the lamp. Typically, this striking voltage is in the region of 3000V to 4500V and the striking pulse needs much more energy than for fluorescent lamps. For this reason the switching device is always referred to as the 'ignitor'.

There are two types of ignitors used for high pressure discharge lamps.

- ***Impulse type ignitor*** - this is a switching device that is connected to part of the ballast coil inducing it to operate as a high voltage transformer to generate sufficiently high voltage to strike the lamp. The ballast itself also experiences these very high voltages and requires strong insulation to prevent internal short circuiting. This type of ignitor is mainly used where the lamp is some distance from the control gear, such as tall lamp posts where the control gear is in the base of the column and the lamp is 20m – 30m up in the lamp-house. 2 wire impulse reactor - ignitor circuit shown below:

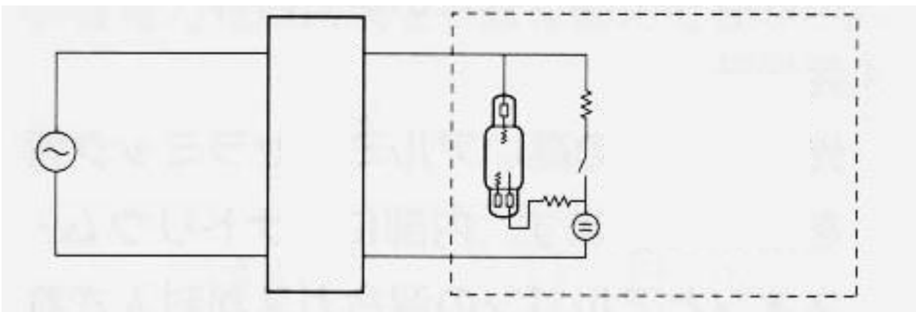


- ***Super-imposed pulse ignitor*** - this is in essence a high voltage transformer, the voltage pulse of which is super-imposed on the mains voltage across the ballast. The ballast is not exposed to high voltages as in the case of impulse type ignitors, so ballast life is generally longer. Super-imposed pulse ignitors are not suitable for remote siting and must be within a 2m – 3m cable length from the lamp. 3 wire super-imposed pulse ignitor circuit shown below:



- Used for “European” MH lamps and most Sodium lamps
- 3.5 - 5 kV pulse
- Ignitor must be mounted within 1 metre of lamp

- ***Internal Ignitor -*** Some high pressure sodium and metal halide lamps have 'internal' ignitors that consist of a bi-metal switch inside the lamp envelope. At switch on, the mains voltage is across this switch and as the bi-metal contacts heat up, they spring apart. This rapid breaking of the circuit induces a high voltage across the ballast causing the lamp to strike. Once the lamp runs up, the ignitor stops operating. A typical circuit is shown below:



3.4.3 Types of HID Lamp

3.4.3.1 High pressure mercury lamps

HEADS UP: High Pressure Mercury Lamps and Energy Efficiency

High pressure mercury (or ‘mercury vapour’) lamps are the least efficient of the HID lamps. They are being phased out in various parts of the world, due to their poor efficiency and high mercury content. Reduction or removal of mercury from the environment is a global public health priority as established by the 2013 United Nations Environmental Programme (UNEP) Minamata Convention on Mercury. Australia is a signatory of the Minamata Convention and the Australian Government is currently considering ratification.

Developed in the 1930s, these lamps use mercury metal in an electrical discharge through argon gas at high pressure. Unlike the low pressure discharge in fluorescent tubes, the higher operating pressure makes the mercury produce proportionally more visible light (with a slight green tinge) and less ultraviolet. The residual ultraviolet is converted to visible light by a phosphor coating on the inside of the outer bulb.

High pressure mercury lamps are mostly elliptical in shape with Edison screw bases. Clear tubular and reflector versions are also available but have significantly declined in popularity over the last 10 years.

Some versions have both a tungsten filament and a mercury discharge tube. The filament has a dual role in that it provides instant light at switch-on, and acts as a current controlling device for the discharge tube. These types operate directly from the mains supply without the need for control gear.

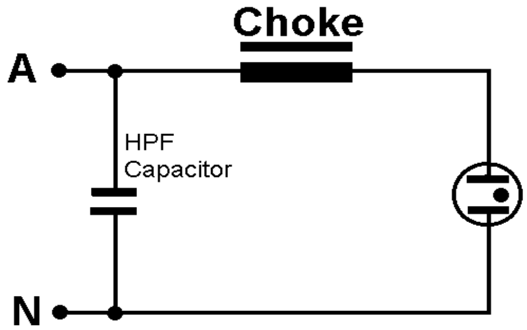
Light is generated by exciting atoms of mercury in an electrical discharge through argon gas. The electricity is conducted through the argon gas between tungsten electrodes at each end of a quartz arc-tube. The electrodes are coated with electron emissive materials similar to those on fluorescent tube cathodes. The operating pressure in the arc-tube is about three times the atmospheric pressure (which is approximately 1,500 times higher than in fluorescent lamps, thus these lamps are called ‘high pressure mercury’). At these operating pressures, mercury atoms produce most of the colours of the visible spectrum, but mostly in the blue and green regions. The light given out is white but with a bluish-green tinge.

The control gear consists of a ballast (also called a ‘choke’) which controls the current through the lamp. A high voltage igniter is unnecessary as these lamps will start at around 170V - well within the 230V peak mains supply voltage.

The self ballasted types (HWL) use the resistance of the series connected filament to control the current through the arc-tube. This means they can be used instead of incandescent lamps.

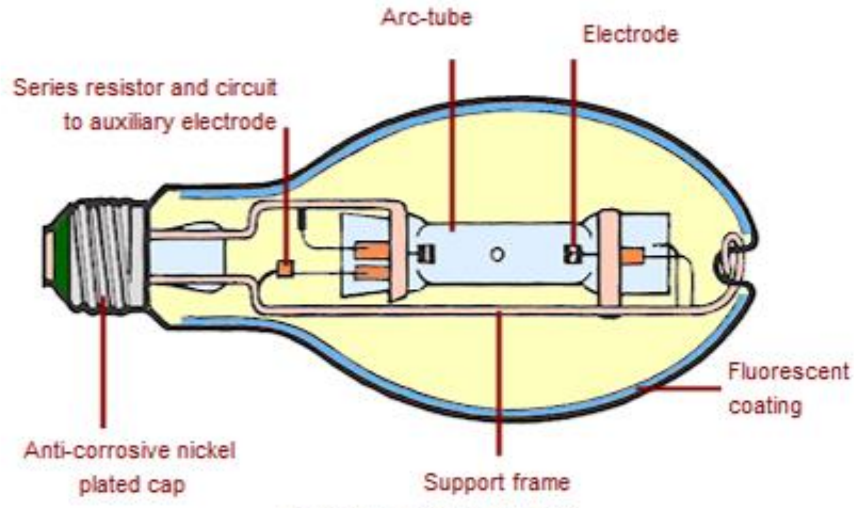
Starting

High pressure mercury lamps do not require starting aids as they will ignite at normal mains voltage, but to make the ignition process easier and more reliable, an auxiliary electrode (sometimes referred to as the starting electrode) is employed to initiate the arc.



The proximity of the auxiliary electrode to the main electrode (only a few millimetres apart) starts a small arc when the lamp is switched on. This starts off the ionisation of the argon gas so that the main discharge can quickly be struck between the electrodes. The current through the auxiliary electrode is kept very small by means of a series resistor in the lamp so that most of the current is carried by the main discharge.

Construction



High Pressure Mercury Lamp

The arc-tube has to be made from quartz (fused silica) because glass would soften and distort under the high operating temperature and pressure. The construction of the quartz arc-tube uses the same pinch-seal technology as for tungsten halogen lamps.

The quartz arc-tube is mounted inside an elliptical glass bulb which is filled with inert nitrogen gas which not only conducts away some of the heat from the arc-tube but also prevents damaging oxidation of the nickel framework supporting the arc-tube. The outer bulb of lamps 250W or greater are made from ‘pyrex’ type heat-resistant glass. Below 250W, the outer bulbs are made from soda-lime glass - the same type of glass used for normal light bulbs.

Approximately 10% of the radiant output from high pressure mercury lamps is ultraviolet. Though it would be safely absorbed by the outer glass bulb, it is not wasted but converted to visible light. The inside of the outer bulb is coated with yttrium vanadate phosphor to convert the ultraviolet to red light which improves the spectral output of the lamp by making the light less dominant in the blue-green region. The white phosphor powder also serves to give the lamp a softer, more diffuse appearance.

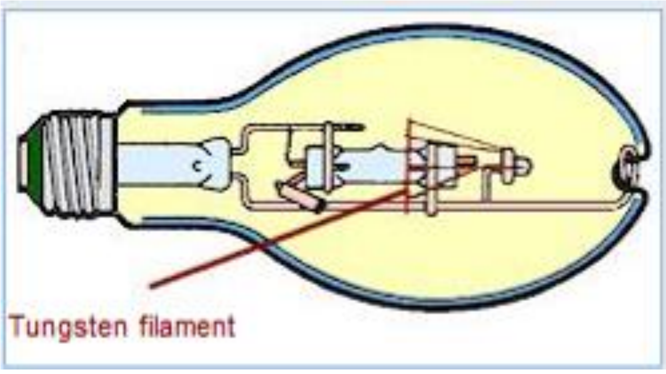
De luxe and super de luxe versions

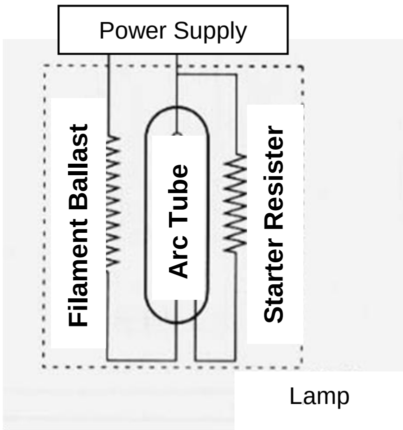
De luxe versions of these lamps have additional yttrium vanadate phosphor to further increase the red output, making the light have a slightly 'warmer' appearance.

Super de luxe versions have an internal golden-yellow powder coating as well as additional phosphor. This gives the lamps an almost 'incandescent light bulb' appearance, but at the expense of a noticeable loss in light output.

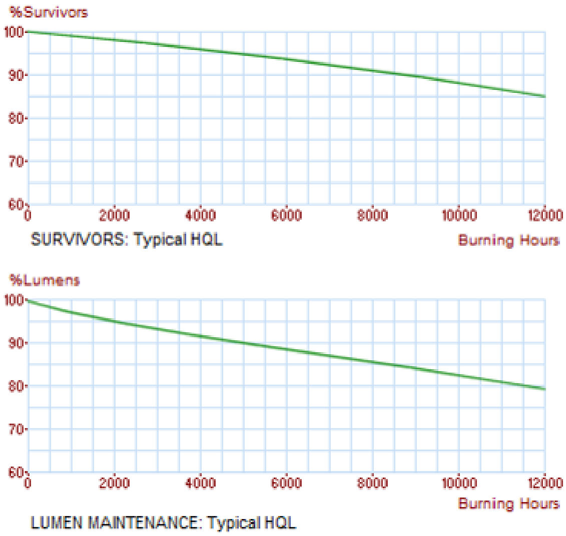
HWL - Mercury Tungsten Blended Lamps

Versions of high pressure mercury lamps that operate directly from the mains supply without the need for control gear have a coiled tungsten filament connected in series with the mercury arc-tube. These are the HWL lamps and are referred to as 'blended' lamps as they blend together incandescent lighting with mercury discharge lighting. The high resistance of the filament acts as the current limiting device for the arc-tube (taking over the function normally performed by the external ballast).





When these lamps are switched on the filament lights begin to dims as the arc-tube warms up to its full light output. This is a useful combination, as these lamps give instant light and, because they don't need separate control gear, can be used as long life replacements for high wattage incandescent lamps. They have an yttrium vanadate phosphor.



Parameter	**Value**
Rated average life	Up to 24,000 hours
Lumen maintenance at 24,000 hours	60%
Luminous efficacy: HQL De lux Super de luxe	 35 – 58 lm/W 40 – 60 lm/W 32 – 46 lm/W

Common notation exists for high pressure mercury lamps, for example Osram notation is HQL or HWL, where:

- *H = Hg (chemical symbol for mercury)*
- *Q = quartz discharge tube*
- *L = leuchtstofflampe (German for fluorescent coating)*
- *W = W (the chemical symbol for tungsten) i.e. tungsten filament*

Applications

High pressure mercury lamps find applications where white light is preferred, colour rendering is of secondary importance but long service life is necessary to avoid the expense of frequent lamp replacement. Typical applications include:

- Industrial lighting
- Sign illumination e.g. motorway signs
- DIY store lighting (though being gradually superseded by metal halide lamps)
- Warehouse lighting
- HWL versions for longer life replacements for high wattage incandescent lamps

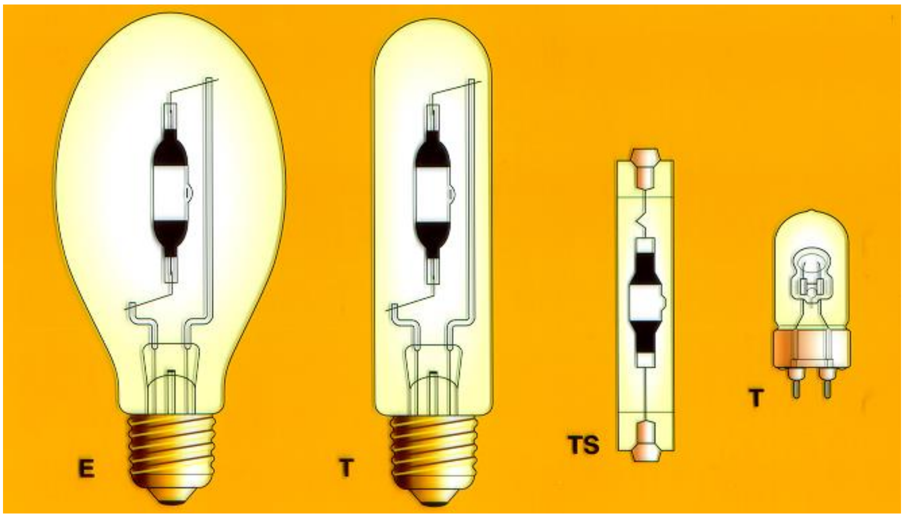
3.4.3.2 Metal halide lamps/ceramic discharge metal halide (CDM) lamps

First developed in the 1960s, metal halide lamps are essentially an improvement on high pressure mercury lamps. The addition of other metal (in the form of halides) to the mercury discharge tube improved the spectral output to give daylight quality white light. The use of quartz for the discharge tube is gradually being overtaken by a ceramic material, which improves the overall performance of the lamps.

They have the greatest luminous efficacy of all HID lamps. Where incandescent (including tungsten halogen) lamps are upgraded to metal halide lamps, there is usually a 75% improvement in luminous efficacy, giving the user both energy saving and improved illumination.

Most metal halide lamps use the same control gear as equivalent wattage high pressure sodium lamps only for operation on phase-to-phase supplies (440V) in some cases. Electronic control gears have been developed for the lower wattage metal halide lamps (up to 150W). These units are small lightweight electronic devices that ignite the lamps and operate them at their optimum performance.

Metal halide lamps come in a variety of shapes and sizes with 2-pin or Edison screw bases. Linear types with contacts at each end are also widely available. Smaller types have quartz outer bulbs whereas the bigger versions employ glass outer bulbs.

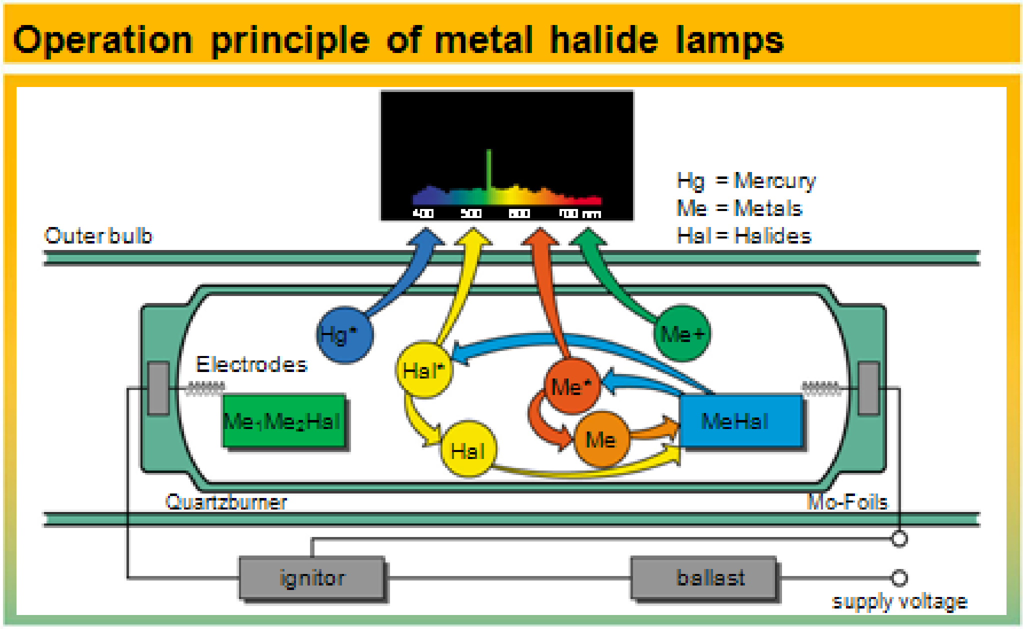


Metal halide lamps are essentially high pressure mercury lamps but with the addition of other metals. When electrically excited, they give a good mix of the primary colours (red, green and blue) across the visible spectrum, to produce white light that is more like natural daylight.

A whole range of different metals are used to ‘fill the gaps’ in the spectral output of mercury. They are excited in an electrical discharge through argon gas operating at a pressure of several atmospheres. The metals are introduced into the arc-tube in the form of halide compounds (usually iodides and bromides). This is done deliberately in order that these halides, when released in the heat of the discharge, take part in a halogen cycle to keep the walls of the arc-tube clear of any deposits of metals, including the tungsten from the electrodes.

Metal used in metal halide lamps

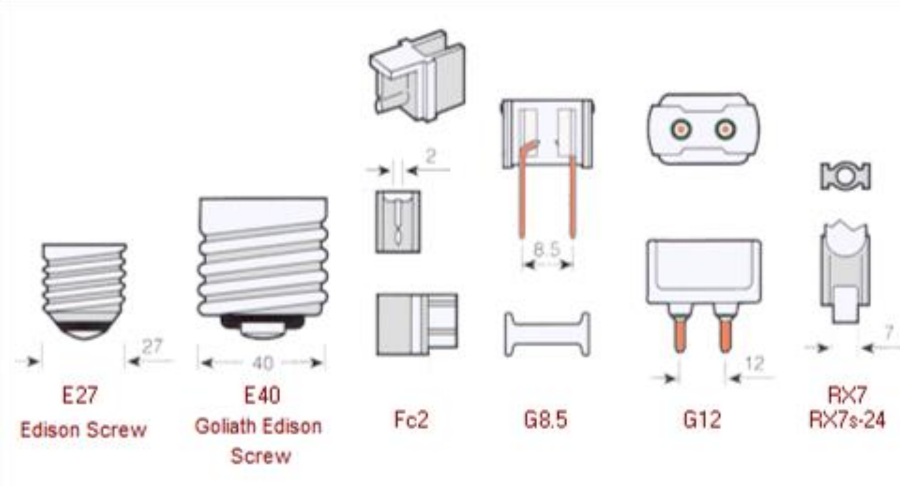
Mercury is the basis of metal halide lamps. Added to the mercury are a 'cocktail' of different metal iodides and bromides. Depending on the requirement for different colour appearances (colour temperatures), different combinations of metals are used in the discharge. For example, sodium, thallium and caesium produce more red light and are used for the 'warmer' colour appearances. Tin, scandium and indium produce more blue light and are used for the 'colder' colour appearances.



Lamp characteristics

The smaller, lower wattage versions also use quartz outer bulbs, but the larger, higher wattage types (>250W), tend to have glass outer bulbs - either tubular or elliptical shaped. Most of these have clear outer bulbs, but some of the elliptical versions have internal white coatings (not phosphors), to produce diffuse lighting.

Those types with quartz outer bulbs employ 2-pin bases (single ended) or end contacts (double ended). All the glass outer bulb versions have Edison screw bases.



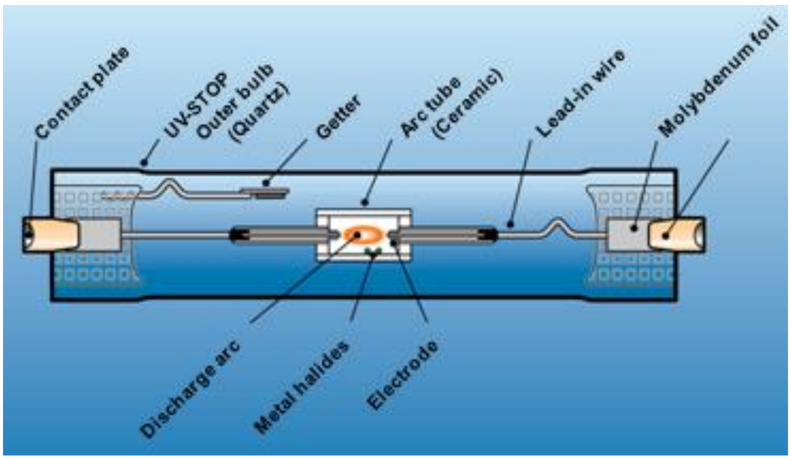
Colour shift

Metal halide lamps were the first discharge lamps to produce daylight quality white light. They are superior to all other discharge lamps as regards their colour rendering capabilities. However, this first generation with its quartz arc-tubes suffers from the problem of changing colour though life - referred to as ‘colour shift’.
This is because the quartz arc-tubes are chemically attacked by alkali metal such as sodium and caesium, causing discolouration of the arc-tube well before the natural end of life of the lamp. The discolouration (browning effect) of the arc-tube and the chemical combination of sodium and caesium with the quartz, alters the spectral output from the lamp. The end result is that the colour appearance of the light changes, usually to a blue-green white light that no longer retains its outstanding colour rendering qualities.

Ceramic technology

The latest technology of metal halide lamps has arc-tubes made from the same material as used in high pressure sodium lamps i.e. ceramic polycrystalline alumina. This material is unaffected by alkali metals and has effectively overcome the problem of ‘colour shift’. This new technology of lamps is known collectively as ‘ceramic metal halide’ lamps.

The first generation of ceramic metal halide lamps uses short cylindrical shaped ceramic arc-tubes. The ends of the arc-tube have thick ceramic plugs to seal in the tungsten electrodes. These plugs absorb much of the light directed towards the ends of the arc-tube, giving the lamp a relatively high radial light output but with little light along the lamp axis.

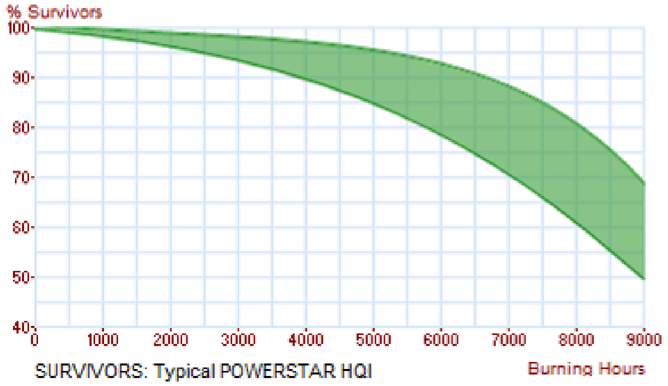


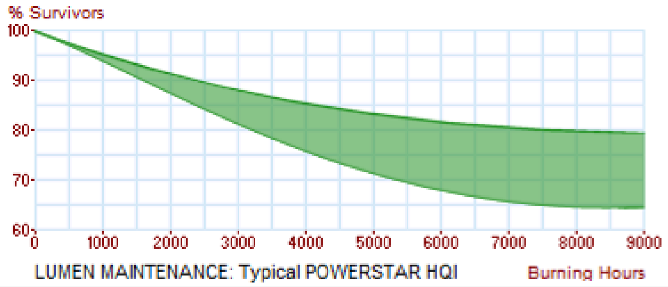
The second generation of ceramic metal halide lamps use a spherical or ball shaped arc-tube. This still retains the excellent colour stability benefit, as well as offering further improvements in light output, lumen maintenance and colour rendering. This later design doesn't have the thick end plugs of the cylindrical arc-tube, which means it produces very uniform light distribution in all directions - making it ideal for use in accurate optical systems.

Ceramic arc-tubes are also incorporated into integral reflector designs to give precisely controlled beam patterns without the need for expensive 'optical control' light fittings.

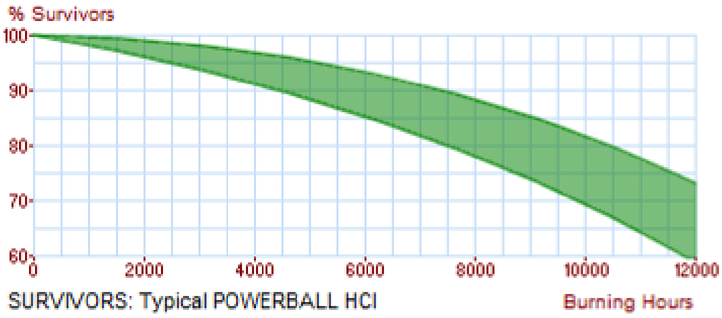
Nominal Mortality and Lumen Maintenance Curves

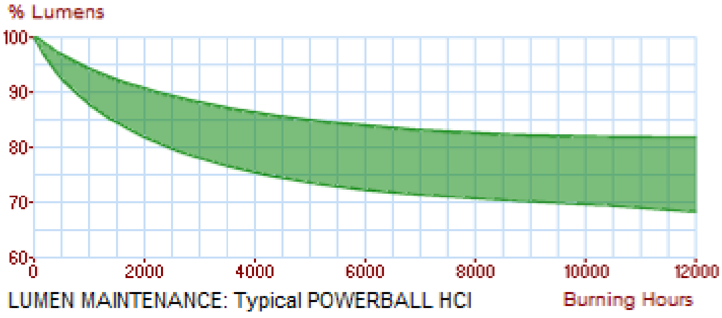
Metal halide lamps are the best of the HID lamps as regards light quality, but their lifetimes and lumen maintenance, though continually improving, are not as good as those of high pressure sodium and high pressure mercury lamps. The introduction of ceramic arc-tube technology has given some increase in both lamp life and lumen maintenance.





Parameter	Value
Rated average life	2,000 – 15,000 hours (dependent on type and wattage)
Lumen maintenance at rated average life	60 – 80%
Luminous efficacy	74 – 100 lm/W





Parameter	**Value**
Rated average life	12,000 hours
Lumen maintenance at rated average life	Exceeds 80%
Luminous efficacy	80 lm/W and above depending on lamp type

The most common notation for metal halide lamps are HQI and HCI, where:

- H = Hg (the chemical name for mercury)
- Q = quartz discharge tube
- C = ceramic discharge tube (cylindrical or spherical)
- I = iodide

Applications

With their daylight quality white light and excellent colour rendering capabilities, metal halide lamps find more uses than any of the other HID lamps. Typical applications include:

- Display lighting (shops, showrooms, museums, exhibitions etc.)
- Stadium lighting (ideal for televised sports events)
- Floodlighting of buildings (especially modern structures with large areas of glass)
- DIY sheds
- Warehouse lighting
- Amenity lighting
- Road lighting (being assessed for lighting of accident black-spots)

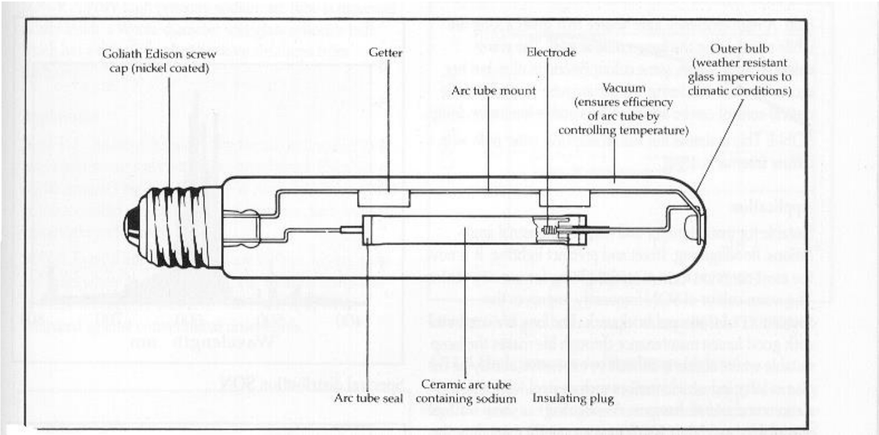
Coloured metal halide lamps, with a special halide content to produce green, blue or magenta-coloured light, give an intense and saturated light that is particularly effective for attractive floodlighting and special display applications.

3.4.3.3 High pressure sodium lamps

These lamps use an alloy of sodium and mercury (called sodium amalgam) in a discharge through xenon gas at a much higher pressure than in SOX lamps. The influence of mercury and xenon is to moderate the deep orange light from the sodium, making it a more whitish orange light. They have clear tubular or elliptical glass bulbs, the latter having a diffuse white coating. All have Edison screw bases. There are also linear versions with contacts at each end (similar to linear tungsten halogen floodlight lamps).

The light from high pressure sodium lamps is produced from the excitations of atoms of both sodium and mercury (from the sodium amalgam), as well as from the atoms of the xenon filling gas. The operating pressure inside the arc-tube is about 80% of ‘high pressure sodium’.

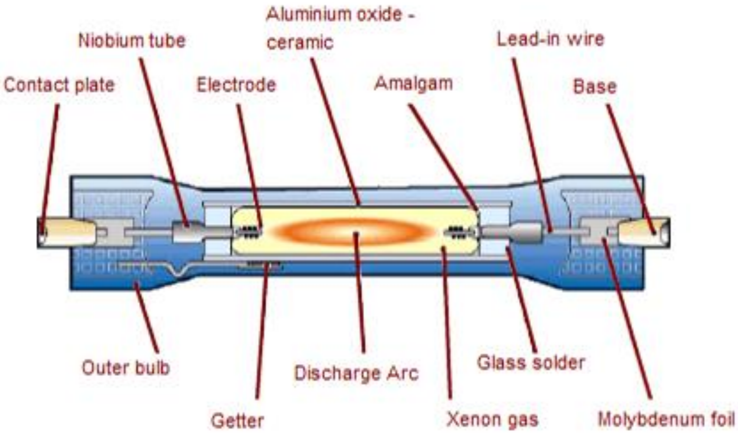
At the higher operating pressure, the mercury produces some blue and red light. Xenon also contributes some blue light, and the combination added to the characteristic orange light from the sodium gives the lamp a whitish orange appearance.



The small arc-tube is made from polycrystalline alumina which is aluminium oxide in ceramic form. This material is transparent to the whitish orange light and resistant to chemical attack from molten sodium.

Tungsten electrodes impregnated with electron emissive material is sealed in at the ends of the arc-tube which is mounted inside a tubular or elliptical shaped outer glass bulb.

All high pressure sodium lamps require an ignition voltage between 3000V - 4500V and a series ballast to control the lamp current. Some high pressure sodium lamps have an internal igniter inside the outer bulb. This igniter operates within a second or two after switch on, and through the ballast induces a series of very high voltage pulses to ignite the lamp. Once the lamp has started, the internal igniter stops operating.



High pressure sodium lamp

Lamp types

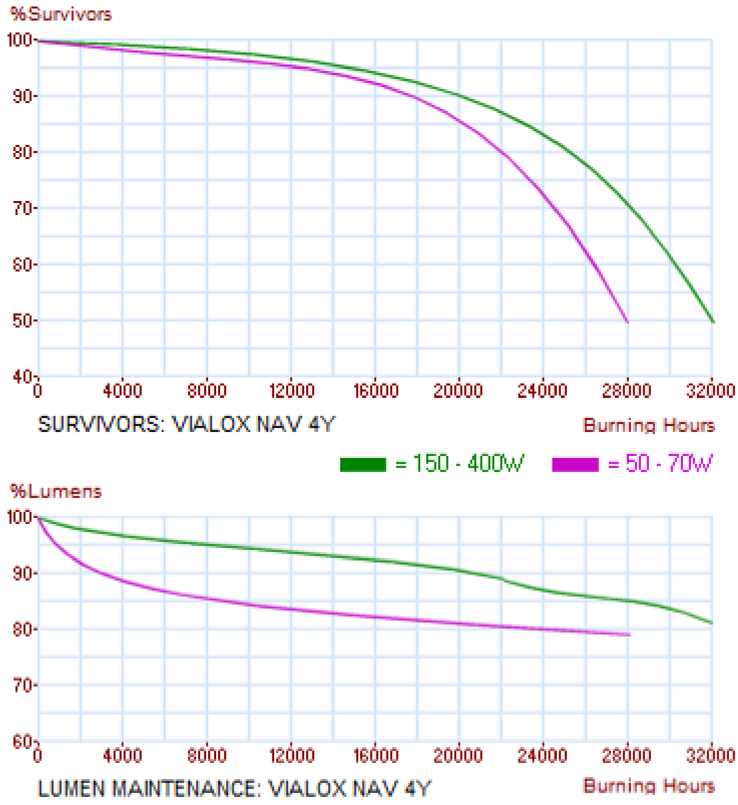
All single ended types have Edison screw bases.

Tubular types always have clear bulbs and the elliptical types generally have a white diffuse coating on the inside. This is not a phosphor coating as these lamps produce very little ultraviolet in the discharge. There are also linear versions using quartz outer bulbs and contacts at each end (similar to linear tungsten halogen lamps).

High pressure sodium lamps come in two grades - standard and super. The 'super' versions offer higher luminous efficacy and improved lumen maintenance compared with the 'standard' versions. The improvement is achieved from having higher xenon gas pressure, but the drawback is that 'super' lamps can be more difficult to start and require good quality igniters.

Nominal Mortality and Lumen Maintenance Curves

High pressure sodium lamps with greatly improved reliability now exist. This offers the user longer service life without the annoying premature failures that require expensive re-lamping before the scheduled group replacement. The service life of these lamps has been increased from 12,000 hours (typically 3 years use) to 16,000 hours (typically 4 years use).



Parameter	Value
Rated average life: 50 – 100 W 150 – 400 W	 28,000 hours 32,000 hours
Lumen maintenance at: 28,000 hours (50 – 100 W) 32,000 hours (150 – 400 W)	 79% 82%

Luminous efficacy: 50 – 100 W 150 – 400 W	 70 - 118 lm/W 84 – 120 lm/W

The important point is that at 16,000 hours (typically 4 years' service life), there are only 5 - 8% failures and more than 90% lumen maintenance.

The common notation for these lamps is SON (a variant of 'sun' because of their better colour rendition). They are also referred to by the acronym 'HPS' lamps.

Applications

Having longer service life and better (though not good) colour rendering, high pressure sodium lamps find a greater variety of uses than SOX lamps. Typical applications include:

- Road and street lighting (gradually replacing SOX lamps)
- Amenity lighting (public areas, car parks etc.)
- Floodlighting of buildings and monuments (the whitish orange light is particularly effective for floodlighting historic buildings)
- Warehouse and cold storage lighting

High pressure sodium lamps with a slightly larger blue component in the spectral output (though this is not discernable to the human eye) are made specifically for horticultural light to promote the growth of plants.

3.4.3.4 Low pressure sodium lamps

Low pressure sodium lamps generate their light by the excitation of sodium metal in a discharge through a mixture of neon and argon gas at very low pressure. With their characteristic deep orange light, these lamps are the most luminous efficient of all HID lamps. All have clear tubular outer bulbs with a bayonet base. However, they have additional insulation between the contact plates to protect against the very high voltages needed to start these lamps.

SOX lamps require a high voltage to start them (sometimes in excess of 600V). They also need to have ballast in series with the lamp to control the lamp current. The normal control gear for SOX lamps is a special transformer that provides the initial high voltage to ignite the lamp and then changes the way it operates to act as a series ballast for controlling the lamp current.

Low pressure sodium (SOX) lamps produce light from the excitation of sodium atoms in an electrical discharge through a mixture of neon and argon gas at very low operating pressure of only about 1% of atmospheric pressure - hence the description 'low pressure'. Because molten sodium is extremely corrosive to both quartz and normal glass, a special sodium-resistant glass has to be used for the arc-tube which is U-shaped and contained in a tubular glass outer bulb - the lengths of which varies according to wattage of the lamp.

Efficiency and heat loss

Heat loss in a SOX lamp is a major consideration. Only about 33% of the input power comes out as visible light, the rest being potentially lost as heat (infrared radiation). To conserve this heat, the inside of the outer glass bulb is coated with a thin film of indium oxide (InO), which has the property of reflecting heat whilst transmitting the orange sodium light.

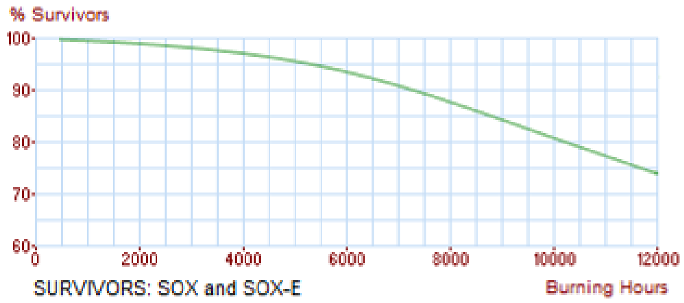
Special SOX economy (SOX-E) versions have a more efficient indium oxide reflecting film, so less heat is lost and more is reflected back onto the arc-tube. With the aid of special control gear, these lamps are the most luminous efficient of all artificial light sources - up to 200 lm/W.

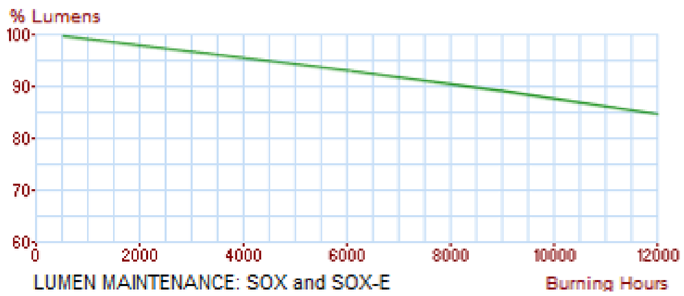
Practical considerations

All SOX and SOX-E lamps use the same bayonet base - BY22d. It is similar but not identical to the one used on conventional incandescent lamps in some countries. The difference is that the BY22d base has a part of the insulation between the contact plates raised up to provide the additional electrical insulation that is required during ignition when voltages in excess of 600V can be generated.

Applications for SOX lamps include economical lighting for arterial roads and motorways, tunnels, car-parks, canals etc. An added advantage is that their monochromatic yellow light attracts few insects (about 5% compared to mercury vapour lamps).

Nominal Mortality and Lumen Maintenance Curves





Parameter	Value
Rated average life	16,000 hours
Lumen maintenance at 16,000 hours	85%
Luminous efficacy: SOX SOX-E	 100 – 175 lm/W 158 – 200 lm/W

The universal notation for these lamps used by all lamp manufacturers is SOX, where:
- SO = sodium
- X = low pressure discharge

They are sometimes also referred to by the acronym 'LPS' lamps.

Applications

Because of their high luminous efficacy but poor colour rendering abilities, SOX lamps are only used where energy efficient lighting is required, without the need for good colour reproduction. This includes:
- Road lighting (especially motorways)
- Industrial lighting (e.g. heavy industry maintenance areas)

3.4.3.5 Xenon discharge lamps

These lamps produce a very intense bluish-white light from an electrical discharge in xenon gas at extremely high pressure.

The light is produced by an electrical discharge through xenon gas at extremely high operating pressure (20 to 30 times atmospheric pressure). They give out a bright bluish white light at the instant of switch on. They use a very thick wall quartz arc-tube to withstand the very high operating pressure but have no outer bulb.

They are not long life lamps (last only a few hundred hours) and are used for very special applications such as medical endoscopes, searchlights and cinema projectors. Instant high light output, XBO lamps are for very special use. Their life and lumen maintenance are less important as they are not used for general lighting.

Applications

The instant crisp blue-white light give xenon discharge lamps certain advantages over other HID lamps in their ability to produce high intensity light immediately at switch on. They are only used for very special applications, including:
- Light source for commercial cinema projectors
- Effect lighting (discos and pop concerts)
- Military searchlights
- Surveillance lighting (on police helicopters)
- Film studio lighting (to simulate daylight in the studio)
- Strobe lighting (strobe lamps are basically xenon discharge lamps)
- Medical endoscopes

3.4.4 HID lamp Run Up Times

Apart from xenon discharge lamps which have instant ignition, all HID lamps take several minutes to reach full light output (although high pressure mercury lamps which have both a tungsten filament and a mercury discharge tube give high immediate incandescent light from the filament). This time is necessary in order that metals in the arc-tube reach the temperature at which they give out their full light output.

The run-up times depend upon the type of lamp and its size. Generally, the smaller lower wattage lamps run-up fastest, and the larger higher wattage versions take longer.

Lamp type	**Run- up times (minutes)**
Xenon discharge	Instant
Metal halide	5 – 8
High pressure mercury	4 – 6
High pressure sodium	2 – 4
Low pressure sodium	12 – 14

3.4.5 HID Lamp Re-strike

Unlike incandescent lamps, HID lamps do not respond to being quickly switched off and on again. Once switched off, they have to cool down to allow the pressure in the arc-tube to fall back to the level that enables the lamp to be re-ignited. This ‘re-strike’ time can be quite long, especially for the larger lamps that take longer to cool down.

Re-strike times vary from about 30 to 90 seconds for high pressure sodium lamps to 5 to 8 minutes for small metal halide and mercury vapour lamps. For the large high wattage metal halide lamps there can be up to 15-20 minute delay. Low pressure sodium lamps have an instant re-strike.

It is possible to ‘hot re-strike’ some metal halide and high pressure sodium lamps, but special control gear is necessary as the ignition voltage required has to be in the region of 25,000V -30,000V. This can only be performed safely on linear double ended lamps, and even then only in light fittings with additional insulation to withstand such high voltages. It may also have an adverse effect on the lamp life.

HID lamps are very sensitive to brief interruptions in the power supply. Whereas incandescent and fluorescent lamps will momentarily go out and come back on again immediately, a break in the power supply of even less than 0.02 sec will cause HID lamps to permanently extinguish. They have to cool down for several minutes, as noted above, before the igniter will start to operate again.

3.4.6 Dimming of HID Lamps

To dim HID lamps it is necessary to run them underpowered. However, HID lamps are designed to be operated within a narrow tolerance of a specific voltage and current to give the claimed light output, power consumption and lamp life. Operating HID lamps outside this tolerance makes them unstable and they are likely to extinguish. Such operation can also damage the electrodes in the arc-tube, which in turn causes the lamp to suffer short life.

The demand for dimming is mainly directed to metal halide lamps. Attempting to dim metal halide lamps causes the arc-tube to operate at a temperature that is too low, which in turn results in the condensation of some of the metal halides. The consequence is a loss of colour from the condensed halides and the overall spectral output of the lamp is changed. The colour temperature changes (usually increases) and the colour rendering index falls significantly. For this reason, dimming of metal halide lamps is not recommended, as the colour and life performance of the lamps cannot be guaranteed.

3.4.7 Safe Operation of HID Lamps

Only high pressure mercury and metal halide lamps have arc-tubes that operate well in excess of atmospheric pressure. Occasionally this can lead to the arc-tube exploding (usually at the end of life).

Sometimes an exploding arc-tube can cause the outer bulb to shatter, dangerously projecting fragments of hot glass and quartz from the light fitting if the latter is 'open', i.e. not enclosed by a toughened glass safety screen. Most light fittings are not equipped with safety screens as these make the light fitting very expensive.

Note: The arc-tubes of high and low pressure sodium lamps operate at much lower pressures and are not prone to explosive failure.

The use of metal halide lamps in areas such as conference rooms, shopping malls, DIY stores, etc. is becoming more popular. Because many of the light fittings used in these areas are the 'open' types (i.e. no safety screen), a range of metal halide lamps has been developed, that are self-protecting and can be safely used in 'open' light fittings.

Inside, the arc-tube is contained in a wire reinforced open ended quartz tube. If the arc-tube should explode, the surrounding quartz tube absorbs the energy of the explosion and slows down the fast moving fragments of the shattered arc-tube, preventing these fragments from destroying the outer bulb. In fact, all the fragments from the arc-tube and the surrounding quartz are safely retained in the outer bulb and none are expelled from the light fitting.

3.4.8 Ultraviolet from HID Lamps

High and low pressure sodium lamps produce small amounts of ultraviolet light which is virtually all absorbed by the outer glass bulbs. They are not classed as being of any serious concern as regards ultraviolet radiation.

High pressure mercury and metal halide on the other hand, do produce relatively high levels of ultraviolet from their arc-tubes. Those versions with glass outer bulbs have the ultraviolet significantly reduced by the filtering effect of the glass and do not pose any health hazard. They can, however, produce a bleaching effect on colour sensitive materials over long periods of exposure.

Metal halide lamps with quartz outer bulbs produce levels of ultraviolet that could be a health hazard, because normal quartz does not filter out ultraviolet radiation. It was always necessary to use ultraviolet filters on light fittings with these lamps. However, some manufacturers now use a special ‘ultraviolet filter’ quartz for their range of metal halide lamps. From a health point of view, these can be used without the need for additional ultraviolet filters on light fittings. However, it may still be prudent to use ultraviolet filters on the light fittings to eliminate the effect of bleaching if the illuminated objects are particularly sensitive (e.g. valuable paintings).

4 Lighting design

HEADS UP: Lighting Design and Energy Efficiency

Good lighting design is often the most overlooked aspect of lighting efficiency, and vice versa.

A lighting installation cannot be efficient AND attractive, without careful consideration of ALL the aspects of lighting design. This includes choice of light source, control gear and luminaire, along with luminaire placement, use of day lighting and intelligent control such as motion detectors and automatic dimming.

Irrespective of whether you are designing a lobby or dining room for a 6-star hotel, an office, or an industrial facility, lighting design must take a holistic approach that not only provides illumination, but creates a comfortable, stimulating and interesting environment.

An efficient and effective lighting system will:

- Provide a high level of visual comfort
- Make use of natural light
- Provide the best light for the task
- Provide controls for flexibility
- Have low energy requirements

Simply achieving the required illuminance does not guarantee a satisfactory lighting installation, and over illumination will not necessarily act as a safety margin. As long as there is adequate illuminance to perform a task, some variation in the level will not generally make a significant change to the level of visual performance. Other aspects of the visual environment such as glare, contrast and user satisfaction will have greater impact on whether a lighting installation is perceived to be successful.

It is therefore important that the quality aspects of the space are addressed in parallel with the illuminance level, namely:

- Correct luminance distribution on the vertical surfaces
- Rational glare control
- Careful treatment of the task surround luminance
- Colour rendering
- Visual interest

Therefore, designing a lighting installation to provide a successful visual environment is a balancing act between multiple requirements which are often conflicting. Add to this the practical limitations of the performance of the light sources and lighting equipment available, energy efficiency, running costs, maintenance and available funds.

Regrettably, the lighting installation is sometimes among the last items to be considered when budgeting a building project, with the result that often cheaper alternatives are chosen just to keep total expenses within financial limits. The outcome may then be less than adequate, giving sub-optimal lighting conditions and low user satisfaction. Proper initial investment in a well designed lighting installation usually repays itself not just in higher return-of-investment but also in lower total cost of ownership during its lifetime.

4.1 Lighting design process

To achieve the best overall outcome in a lighting installation, it is important to avoid the tendency of rushing straight into luminaire selection before determining more broadly what is required from the system. The use of a structured design process helps to avoid this. The key steps in the design process are:

1. Identify the requirements
2. Determine the method of lighting
3. Select the lighting equipment
4. Calculate the lighting parameters and adjust the design as required
5. Determine the control system.
6. Check that the fittings to be installed are those that the design was based on
7. Inspect the installation upon completion and, if possible, a few months after occupation, to determine what worked and what didn't. This is the only way to build up experience to apply to future designs.

The five initial stages are considered in more detail in the following sections.

4.1.1 Identifying the requirements

This involves gaining a full understanding of what the lighting installation is intended to achieve. This includes the:

- Task Requirements
  - Illuminance
  - Glare
- Mood of the space
- Relation to shape of space
- Things to be emphasised
- Things to hide
- Direction of light
- Interaction of daylight

4.1.2 Determine the method of lighting

At this stage, consideration is given to how the light is to be delivered, e.g. will it be recessed, surface mounted, direct or indirect, or will up-lighting be used, and its primary characteristics, e.g. will it be prismatic, low brightness or mellow light. Consideration should be given at this stage to the use of daylight to minimise the need for artificial light.

4.1.3 Select the lighting equipment

Once the method of lighting has been selected, the most appropriate light source can then be chosen followed by the luminaire. The following attributes should be studied when choosing the light source:

- Light output (lumens)
- Total input wattage
- Efficacy (lumens per Watt)
- Lifetime
- Physical size
- Surface brightness / glare
- Colour characteristics
- Electrical characteristics
- Requirement for control gear
- Compatibility with existing electrical system
- Suitability for the operating environment

A number of factors also affect luminaire choice:

- Characteristics of the light source and control gear (see above)
- Luminaire efficiency (% lamp light output transmitted out of the fixture)
- Light distribution

- Glare control
- Finish and appearance
- Size
- Accessibility of components for maintenance
- Ability to handle adverse operating conditions
- Aesthetics
- Thermal management

4.1.4 Calculate the lighting parameters

Lighting calculation methods fall into three broad categories:

- Manual calculation methods
- Three dimensional modelling
- Visualisation

Photometric data for light sources and luminaires is commercially available to contribute to these calculations.

4.1.4.1 Manual calculation methods

There are a wide range of manual computation methods for the calculation of different lighting aspects. These include complex methods for calculating the illuminance from a wide variety of shapes of luminous objects. The majority of these have now been superseded by computer programs.

The Lumen Method was the mainstay for interior lighting and has remained in use as a quick and relatively accurate method of calculating interior illuminance. The Lumen Method calculates the average illuminance at a specific level in the space, including an allowance for the light reflected from the interior surfaces of the room. The calculation method has a set of assumptions that, if followed, gives a reasonable visual environment. Inadequate attention to the assumptions will produce poor results. The basic assumptions are:

- All the luminaires in the room are the same and have the same orientation
- The luminaires do not have a directional distribution and are aimed directly to the floor
- The luminaires are arranged in a uniform array on the ceiling and have the same mounting height
- The luminaires are spaced less than the maximum spacing to mounting height ratio nominated in the coefficient of utilisation tables

The average illuminance produced by a lighting installation, or the number of luminaires required to achieve a specific average illuminance, can be calculated by means of utilization factors, a UF being the ratio of the total flux received by a particular surface to the total lamp flux of the installation.

4.1.4.1.1 Lumen method formula

The average illuminance E(h) over a reference surface s can be calculated from the "lumen method" formula.

$$E(h) = \frac{F \times n \times N \times LLF \times UF(s)}{\text{area of surface } s}$$

where:

F = the initial bare lamp flux (lumens)

n = the number of lamps per luminaire

N = the number of luminaires

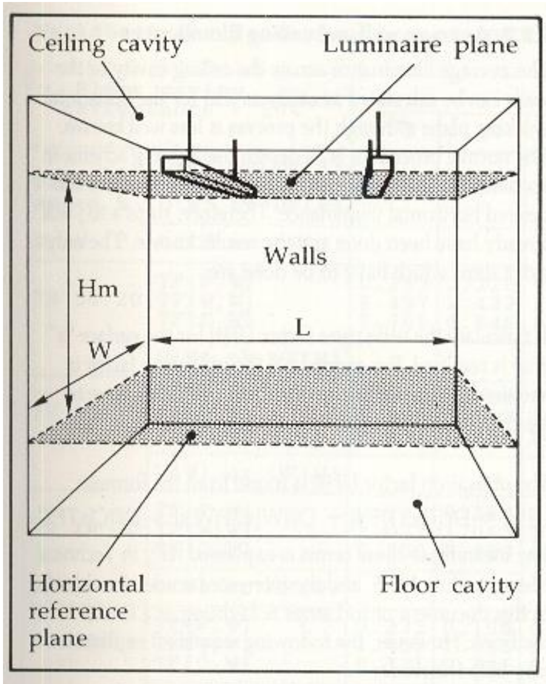
LLF = the total light loss factor

UF(s) = the utilization factor for the reference surface s of the chosen luminaire

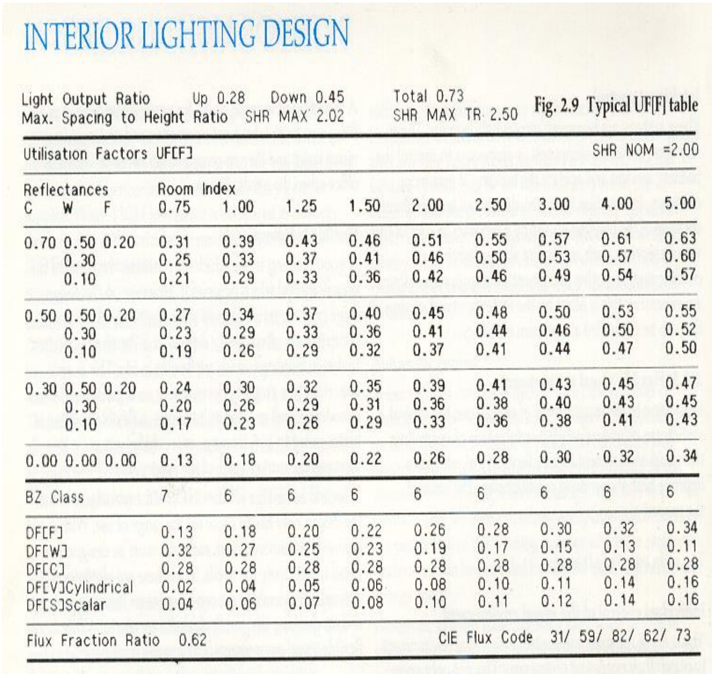
Utilization factors can be determined for any surface or layout of luminaires. The "UF" symbol is normally shown followed by an extra letter in brackets, to denote the surface, for example, UF(F) is the utilisation factor for the floor cavity and UF(W) is the utilisation factor for the walls.

Utilization factors are, in practice, only calculated for general lighting systems with regular arrays of luminaires and for three main room surfaces. The highest of these surfaces, the C surface (for ceiling cavity), is an imaginary horizontal plane at the level of the luminaires having a reflectance equal to that of the ceiling cavity. The lowest surface, the F surface (for floor Cavity), is a horizontal plane at normal working height (i.e. table height), which is often assumed to be O.85m above the floor. The middle surface, the W surface (for walls), consists of all the walls between the C and F planes.

Although the lighting designer can calculate utilization factors, lighting companies publish utilization factors for standard conditions for their luminaires. The standard method of presentation is shown below. To use this table, it is only necessary to know the Room Index and the effective reflectance of the three standard surfaces (floor cavity, walls and ceiling cavity).



Room Index Calculation



INTERIOR LIGHTING DESIGN

Light Output Ratio Up 0.28 Down 0.45 Total 0.73
Max. Spacing to Height Ratio SHR MAX 2.02 SHR MAX TR 2.50

Fig. 2.9 Typical UF[F] table

Utilisation Factors UF[F] SHR NOM =2.00

Reflectances C W F	Room Index 0.75	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
0.70 0.50 0.20	0.31	0.39	0.43	0.46	0.51	0.55	0.57	0.61	0.63
0.30	0.25	0.33	0.37	0.41	0.46	0.50	0.53	0.57	0.60
0.10	0.21	0.29	0.33	0.36	0.42	0.46	0.49	0.54	0.57
0.50 0.50 0.20	0.27	0.34	0.37	0.40	0.45	0.48	0.50	0.53	0.55
0.30	0.23	0.29	0.33	0.36	0.41	0.44	0.46	0.50	0.52
0.10	0.19	0.26	0.29	0.32	0.37	0.41	0.44	0.47	0.50
0.30 0.50 0.20	0.24	0.30	0.32	0.35	0.39	0.41	0.43	0.45	0.47
0.30	0.20	0.26	0.29	0.31	0.36	0.38	0.40	0.43	0.45
0.10	0.17	0.23	0.26	0.29	0.33	0.36	0.38	0.41	0.43
0.00 0.00 0.00	0.13	0.18	0.20	0.22	0.26	0.28	0.30	0.32	0.34
BZ Class	7	6	6	6	6	6	6	6	6
DF[F]	0.13	0.18	0.20	0.22	0.26	0.28	0.30	0.32	0.34
DF[W]	0.32	0.27	0.25	0.23	0.19	0.17	0.15	0.13	0.11
DF[C]	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
DF[V]Cylindrical	0.02	0.04	0.05	0.06	0.08	0.10	0.11	0.14	0.16
DF[S]Scalar	0.04	0.06	0.07	0.08	0.10	0.11	0.12	0.14	0.16

Flux Fraction Ratio 0.62 CIE Flux Code 31/ 59/ 82/ 62/ 73

Typical Co-Efficient of Utilisation Table

4.1.4.1.2 Room Index

The Room Index is a measure of the angular size of the room, and is the ratio of the sum of the plan areas of the F and C surfaces to the area of the W surface. For rectangular rooms the room index is given by:

$$\mathbf{RI} = \frac{\mathbf{L \times W}}{\mathbf{(L+W)Hm}}$$

Where:

L = the length of the room
W = the width of the room
Hm = the height of the luminaire plane above the horizontal reference plane.

If the room is re-entrant in shape, for example L shaped, then it must be divided into two or more non-re-entrant sections, which can be treated separately.

4.1.4.1.3 Spacing to Mounting Height Ratio

The Spacing to Mounting Height Ratio (SHR) is the spacing between luminaires divided by their height above the horizontal reference plane. It affects the uniformity of illuminance on that plane. When the UF tables are determined, for a nominal spacing to height ratio SHR NOM, the maximum spacing to height ratio SHR MAX of the luminaire is also calculated, and is a value that should not be exceeded if the uniformity is to be acceptable.

4.1.4.2 Three dimensional modelling

Although it was possible to calculate the luminance of all the surfaces in a room, the calculations were extremely laborious and could only be justified in the most special cases. However, the advent of computer modelling enabled a more flexible approach to lighting design and significantly increased the information available to the designer.

In contrast to the Lumen Method, lighting programs enable the lighting designer to broaden the assumptions:

- A mixture of luminaires can be used
- The luminaires no longer have to be arranged in a regular array
- Directional luminaires can be modelled
- A large number of calculation points can be considered to give a meaningful uniformity calculation
- The illuminance and luminance of all surfaces can be calculate

This gives the lighting designer a much greater understanding of what is happening in the room. However there has been considerable research, experience and documentation over the past 80 years that has developed the current thinking in the adequacy of various illuminance levels for various tasks and functions. Although there is some general understanding of the need for appropriate luminance distribution in the vertical plane, there is little information, experience or understanding for many designers to determine:

- What the luminance of surfaces should be in varying situations
- What is an acceptable luminance uniformity
- Whether there should there be a maximum luminance uniformity
- What is the desired graduation in luminance
- At what point is the luminance distribution of the wall unacceptable

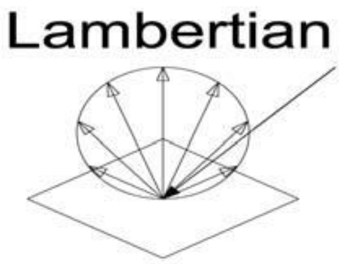
It is important in using a lighting calculation program that the output records the type of luminaire used, the location of the luminaires, the assumed lumen output of the lamp, the light loss factor and the aiming points. If this is not recorded you have a pretty picture of the installation and no way of making it a reality.

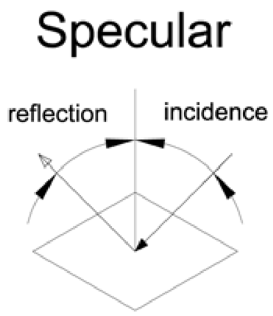
4.1.4.3 Visualisation

These are programs that create a perspective rendering of the space in levels of detail that vary from a block representation of the space, to photographic quality renderings, depending on the sophistication of the program and the level of detail of the interior to be entered. The programs fall into two basic types:

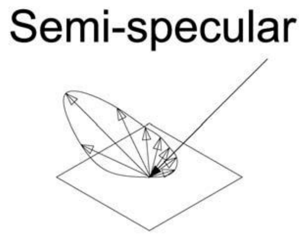
- Flux transfer or radiosity calculations
- Ray tracing calculations

The major difference being in how they interpret light from reflective surfaces. A Lambertian surface is a perfect diffuser, where light is reflected in all directions, irrespective of the angle of incidence of the light such that irrespective of the viewing angle the surface has the same luminance. A specular surface is a mirror like surface, where the angle of reflection of the light is the same as the angle of incidence.





A real life surface is a combination of both surfaces (semi-specular) and has both specular and diffuse characteristics. Some materials are more specular while others are more diffuse.



A **flux transfer or radiosity** program treats all surfaces as diffuse or Lambertian surfaces, as a result their rendering tends to appear flat with soft shadow details. It will tend to overestimate the uniformity.

Ray tracing traces the individual rays of light from the source to the eye as it reflects from surface to surface around the room. As a result ray tracing can allow for the specular component of the surfaces.

Some programs calculate the entire lighting by ray tracing while others calculate the space on a flux transfer basis and have an overlay of ray tracing of specific areas to improve the quality of the rendering. When ray tracing is added, reflections are added in polished surfaces and shadows become sharper.

Visualisation programs are a useful tool in the presentation of a design, as a tool for the designer to check that the design is consistent with his own visualisation of the space, and to model specific lighting solutions. The programs are still calculation tools and not design programs. The programs can show the designer how a specific design will perform but that they cannot reliably be used to assess the acceptability of a design.

Irrespective of the form of the visualisation output, it is important that the program provides adequate information to enable the construction and verification of the lighting design.
The output should include:

- ***Installation information*** **-** the type and location of all luminaires and the aiming information. The lamp details should be included as well as the specific catalogue number of photometric file that has been used.
- ***Light technical parameters*** – the illuminance, uniformity and other parameters that have been calculated to achieve the design.
- ***Verification information*** – adequate details to enable the lighting calculation to be verified. This should include the luminaire type, the photometric file, surface reflectances that were assumed, light loss factors, lumen output of lamps and mounting and aiming locations.

4.1.5 Determine the control system

The effectiveness and efficiency of any lighting installation is affected as much by the control system as by the light sources and fixtures chosen. Give consideration to:

- Providing multiple switches to control the number of lights that come on at any one time. Using one switch to turn on all the lights in a large room is very inefficient.

- Placing switches at the exits from rooms and using two-way switching to encourage lights to be turned off when leaving the room.
- Using ‘smart’ light switches and fittings which use movement sensors to turn lights on and off automatically. These are useful in rooms used infrequently where lights may be left on by mistake, or for the elderly and disabled. Make sure they have a built-in daylight sensor so that the light doesn’t turn on unnecessarily. Models which must be turned on manually and turn off automatically, but with a manual over-ride, are preferable in most situations. Be aware that the sensors use some power continuously, up to 5W or even 10W in some cases.
- Using timers, daylight controls and motion sensors to switch outdoor security lights on and off automatically. Controls are particularly useful for common areas, such as hallways, corridors and stairwells, in multi-unit housing.
- Using solar powered lighting for garden and security lights.
- Using dimmer controls for incandescent lights (including halogens). This can save energy and also increase bulb life. Most standard fluorescent lamps cannot be dimmed, but special dimmers and lamps are available. If lamps are to be dimmed it is important to ensure that the correct equipment is used, especially when retrofitting more energy efficient lamps.

4.1.6 Choice of Luminaire

The performance of a luminaire should be considered just as carefully as its cost. In the long term a well designed, well constructed luminaire will be cheaper than a poor quality unit; and the salient features of a good quality luminaire are:

* Sound mechanical and electrical construction and a durable finish
* Adequate screening of high luminance lamps to minimise discomfort and glare
* Adequate heat dissipation to prevent over-heating of the lamp, wiring and ancillary equipment
* High light output ratio with the appropriate light distribution
* Ease of installation, cleaning and maintenance

4.2 Standards, Codes and Regulations

4.2.1 Australia - National Construction Code

When designing lighting systems, there are some specific standards and codes that must be taken into account. These provide useful advice and guidance as well as specifying any mandatory requirements.

Minimum Energy Performance Standards (MEPS) already apply to certain items of equipment in the lighting industry. This ensures that when these items are manufactured they meet the performance standards.

In May of 2006 the Australian Government introduced a mandatory section for maximum energy requirements in new buildings through the National Construction Code. The particular reference to lighting is in Section J6 which details the maximum values of lumens per watt (lm/w) and watts per square metre (w/m^2) allowable for certain building classes and tasks performed.

Building classes are listed below

- **Class 1a** — single dwelling, row house, terrace house, townhouse or villa
- **Class 1b** — boarding house or guest house < 300m^2 or 12 persons
- **Class 2** — sole-occupancy units
- **Class 3**: — residential, boarding house, hostel, motel, residential part of aged care, school or health care
- **Class 4**: — caretakers dwelling
- **Class 5**: —office

- **Class 7a** — carpark
- **Class 7b** — wholesale warehouse or storage facility
- **Class 8**: — laboratory or factory
- **Class 9a** — health-care building
- **Class 9b** — assembly building
- **Class 9c** — aged care facility
- **Class 10a** — non-habitable private garage, shed, carport or the like
- **Class 10b** — swimming pool, mast, antenna, fence, retaining wall

The *Deemed-to-Satisfy* provisions are based on limits to the following parameters:

- Lamp power density (W/m^2) means the total of the maximum power rating of the lamps in a space, other than those that are plugged into socket outlets for intermittent use such as floor standing lamps, desk lamps or work station lamps, divided by the area of the space.
- Illumination power density (W/m^2) means the total of the power that will be consumed by the lights in a space, including any lamps, ballasts, current regulators and control devices other than those that are plugged into socket outlets for intermittent use such as floor standing lamps, desk lamps or work station lamps, divided by the area of the space.
- Light source efficacy means the luminous flux of a lamp or the total radiant flux in the visible spectrum weighted by the spectral response of the eye, divided by the electric power that will be consumed by the lamp but excluding ballast and control gear power losses.

The provisions in the National Construction Code are updated regularly. The code can be downloaded free of charge from www.abcb.gov.au

4.2.2 Australia - Commercial Building Disclosure

In Australia, commercial buildings (or parts thereof) that are 1000 square metres in size or greater are subject to commercial building disclosure legislation, at the time of sale or lease. This means that the building, or space within, is required to have a Building Energy Efficiency Certificate (BEEC) before it is put to the market for sale or lease as well as the National Australian Built Environment Rating System (NABERS) Energy star rating on all of its advertising material. BEECs are valid for up to 12 months, must be publicly accessible on the online register at and include:

- a National Australian Built Environment Rating System (NABERS) Energy star rating for the building
- an assessment of the energy efficiency of tenancy lighting in the area of the building that is being sold or leased.

The tenancy lighting assessment involves a quantitative assessment of the illumination power density of the space(s) as well as a qualitative assessment of the lighting control system and potential for upgrading the lighting system to improve efficiency. More information at http://cbd.gov.au.

4.3 Australian Lighting Standards and Their Relevance

The human eye will adapt to an enormous range of illumination levels. The untrained eye cannot easily detect a 20% change in illumination levels. In a general office or home environment we read under levels ranging from 50 lux to 1000 lux. We can also read at night on the railway station platform with only 15 lux and conversely outside on a sunny day in illumination levels of 100,000 to 150,000 lux.

However there is an optimum level which will produce the greatest "task efficiency" with the lowest practical illumination level. To ascertain the 'correct' illumination level for any given task extensive research has been carried out comparing various illumination levels with a person's task efficiency or work output under the different illumination levels. The results of these studies are the basis of the Australian/New Zealand Standard for Interior Lighting AS/NZS 1680 series. The illumination levels recommended in this standard are the minimum recommended illumination levels to be maintained that will permit consistently high task efficiency with comfortable intensity levels.

As previously discussed, the first step in providing the correct solution is to identify the needs of the site. Minimum illumination levels for various applications should be checked with the Australian Standard and the type of luminaire which best suits the glare control limits required can be selected. The Standard generally recommends ***MINIMUM*** maintenance illumination levels only. It is also accepted that corporate requirements, or unusual circumstances, may require higher levels in various situations.

It is worthy of note that the highest recommended illumination level in the Interior Lighting Standard is 1600 lux, which is recommended for minute instrument workings inspection such as watch making.

The key standards are:

- AS1680.1-2006, '*Interior and workplace lighting - general principles and recommendations*'
- AS/NZS 1680.2 series, '*Interior and workplace lighting - specific applications*'

A brief overview of the Australian Standards for lighting is given in Appendix 1.

4.4 Building in efficiency

As lighting accounts for a significant percentage of energy use there is an increasing requirement to achieve the required visual environment while minimising energy use and consequential greenhouse gas emissions.

Energy efficient lighting is not simply minimising the energy input through higher equipment efficiency, or reducing illuminance levels to the minimum that is tolerable. If user comfort is poor, then there a likelihood that occupants will increase illuminance levels (for example with desk lamps) to compensate.

In most cases, LED lighting is now the most energy efficient form of lighting for households. LED lamps use only about one quarter of the energy used by halogen lamps to provide the same light level.

Although more expensive to buy they are much cheaper to run and can last between 15,000 to 50,000 hours. With careful design they can replace incandescent, halogen and fluorescent lights in most situations.

4.5 Use of daylight

The most energy efficient light is natural light. The science of day lighting involves the deliberate use of daylight to displace electric light. Large savings are possible in offices and other non-residential buildings when the relative amounts of daylight and artificial light are regulated by sensors and a control system. Done correctly, there will be a net saving of energy consumed by the building. Done incorrectly, the heat load on the building will increase and there will be a net increase in cooling energy consumption. If the daylight control system is poorly implemented, building occupants deal with glare and/or thermal discomfort using the most expedient means at hand, which in turn usually cancels out any of the benefits that day lighting might have offered.

In a residential setting, well designed north-facing windows, skylights and light tubes let in light without adding to summer heat and winter cold. Light coloured interior surfaces, especially in south-facing rooms and hallways, reflect more light and reduce the level of artificial lighting required.

Effective use of daylight depends on many factors including:

- The sun's altitude and azimuth
- The relative occurrence of overcast versus sunny weather
- The season
- Levels of air pollution and haze

Australian cities are not afflicted by heavy air pollution as much as many overseas locations, except on isolated occasions such as during severe bushfires or dust storms. Therefore it is possible to predict average sky conditions with good accuracy, including relative amounts of clear and overcast sky, for most populated locations.

An essential starting point in day lighting design is to determine the distribution of sunlight and shadow on the site. Phillips (1983) provides solar charts for latitudes from Darwin to Hobart, together with a useful shadow-angle protractor. Several well-known references provided tabulated data for sky conditions for major Australian centres and how to use the knowledge to design effective sky lighting. Good day lighting designers must also be mindful of reflected glare from neighbouring buildings; Hassall (1991) gives extensive advice and methods for predicting and avoiding 'rogue reflections' from nearby buildings, etc.

Locations with a high incidence of cloudy skies are better served by roof windows or conventional skylights with large areas and diffuse glazing systems. On the other hand, sunny locations can exploit tubular day lighting devices – tubular skylights – which send direct-beam sunlight into the space below and are capable of delivering very high illumination levels provided the sky is clear.

5 Selling efficiency and replacement technologies

HEADS UP: Selling Efficiency

The trend toward energy efficiency has taken a quantum leap in recent years, with the demand for energy efficient equipment and appliances being largely consumer driven. The objective of this manual is to give electricians, salespeople and anyone involved in lighting, a range of tools to specify and install efficient, high quality lighting systems. The benefits to consumers are lower running costs, reduced environmental impact and often improved lighting quality which comes from thoughtful lighting design, rather than adherence to out-dated (yet easy) lighting practices.

With the phase out of incandescent lamps in Australia it is necessary to replace incandescent (and possibly halogen) lamps with a more energy efficient alternative. In the residential sector this will normally be a direct replacement with LED lamps or luminaires, or some form of fluorescent technology. In new build installations, there is greater freedom of choice and flexibility and the opportunity to further minimise energy consumption by good lighting designing. In both instances, consideration should be given to a few key points.

The Australian Government has released a smartphone app to provide consumers with information about upgrading household lamps - more information is available at http://www.energyrating.gov.au/apps.

5.1 Suitability

At a basic level, when selecting lamps it is important to ensure that they are compatible with the fixtures and circuits that are already in place (or that are included in the design). For example, do you need a particular lamp base (pin base, Edison screw base, bayonet) or does the linear fluorescent tube chosen require a particular fitting (e.g. T5 fluorescent tubes are not interchangeable with T8 or T12 tubes). More generally, several other points should be considered.

5.1.1.1 Point source – non-point source

The nature of the task that the lamp is required to perform is an important consideration. If an object or a location specific task is to be illuminated, a point source is recommended (suitable LED). However, for more general lighting a more diffuse (non-point source) can be used which will light the entire space (LED, linear fluorescent or CFL).

5.1.1.2 Directional – non directional

If more control the area being illuminated is required this can be achieved by using a directional light source. These lamps use either an integral reflector or a reflector built into the luminaire to restrict the passage of light backwards from the light source and reflect it forwards.

5.1.1.3 Size

Although energy efficient lamps are increasingly becoming available in a wide range of shapes and sizes, care should still be taken when selecting replacement lamps to ensure that they are a suitable size for the luminaire or fixture in which they are being used. With integral ballast CFLs, the extra required for the ballast can result in a lamp with an equivalent bulb size to the one that is being replaced failing to fit the luminaire. LEDs are less likely to exhibit this problem.

5.1.1.4 Colour temperature

The colour temperature of a lamp determines the colour that the light source appears. There are several reasons for selecting a particular colour of lamp.

Atmosphere – incandescent and halogen lamps have traditionally been used in homes and hotels. As a result the warmth and reddish appearance tends to be associated with comfort and relaxation. In these types of installations and areas where people are to be encouraged to relax, a lamp with a colour temperature of 2,700K to 3,000K would be preferable. As low colour temperature lamps give an atmosphere of warmth, they are often preferred for cooler climates. In areas that are hot or humid and not air conditioned, moving to a cooler lamp, around 4,000K or higher, can reduce the oppressive feeling.

Colour Scheme – irrespective of the colour rendering of the lamps, the correlated colour temperature needs to be co-ordinated with the colour scheme of the room. In many colour schemes it has little effect, however where warm lamps are used with a cool colour scheme or vice versa, the general feeling of space can be incongruous. It can be a particular problem where mid greys are used, as the spectral difference between a warm grey and a cool grey can be slight.

Matching with other sources – There is a general preference to match the colour of light sources throughout an installation, as significant variations in the colour appearance draws attention to the light fittings. However, changes in the colour appearance of lamps can be used to advantage. When highlighting an object a subtle shift in colour appearance to the cooler temperature can help draw attention, thereby requiring a smaller contrast in luminance. Also, a reduction in colour temperature when moving from a work area to a relaxation area can increase the contrast in the atmospheres and reinforce the change in role.

5.2 Compatibility

Retrofitting more energy efficient lamps introduces some additional compatibility considerations.

5.2.1 Think lumens, not watts

We used to purchase old fashioned incandescent bulbs by the amount of power (or watts) they used. With the energy-efficient new technologies now available, such as LEDs, light bulbs now produce the same amount of light using far less power. It no longer makes sense to shop for watts. Using ‘lumens’ is now the way to choose the amount of light required.

Lumens give a measure of the amount of light produced by a light bulb. An old-fashioned incandescent light bulb (no longer available) produced 700 lumens and used 60W of power, whereas a new energy efficient LED uses only 10W. Also, halogen lamps will be less efficient and cost more to run than CFL (compact fluorescent lamp) and LED (light emitting diode) equivalent options.

The table below shows the required lumen output of an LED, when used to replace old style incandescent and halogen light bulbs. Also shown are the typical wattages of bulbs.

LED Light Output (Lumens)	Power (Watts)			
	Old style incandescent	Mains voltage halogen	CFL	LED
250	25	18	4-6	3-4
500	40	28	7-9	5-8
800	60	42	11-14	8-12
1100	75	52	14-17	11-17
1500	100	70	19-23	15-23

5.2.2 Thermal issues – over heating

When introducing new lamps into an existing lighting system, the space around the lamp is fixed. This therefore means that the space available for heat dissipation is also restricted. Care should therefore be taken when choosing replacement lamps to ensure that they do not generate more heat during operation than can easily be dissipated in the space available. LEDs are especially sensitive to higher temperature environments, as they have difficulties with heat dissipation. The hotter the LED gets the worse it performs. Check the package, data sheet, or seek advice from the supplier regarding the suitability of LED products in high temperature environments.

5.2.3 Dimmability

Over recent years there has been an increase in the popularity of dimmers fitted to lighting circuits. This can pose constraints on the choice of lamps to replace incandescent and halogen lamps, as fluorescent and LED lamps may not be compatible with dimmers designed for incandescent/halogen lamps.

Some compact fluorescent lamps are not compatible with existing dimming circuits – the lamp will not work properly and the electronics in the dimmer switch could be damaged. It is recommended that you refer to product packaging at the time of purchase, or alternatively contact the manufacturer for product specific information. However, specialised integral ballast CFLs which are compatible with dimming circuits are available and more dimmable compact fluorescent lamps are expected to become available as the phase-out of incandescent lamps progresses.

Some LED lamps may not be compatible with existing lighting systems that include a dimmer circuit, resulting in the LED lamp not operating satisfactorily (flickers, restricted dimming). Older dimmers (using leading edge technology) are likely to be the most problematic, with more recent models using trailing edge technology having a high level of compatibility with LED dimmable lamps. Leading edge dimmers were designed to work with filament lamps and magnetic transformers and are generally not recommended for LED lamps. Trailing edge dimmers were developed for compatibility with electronic transformers (introduced in late 1990s) and this dimmer type is generally regarded as the better type to operate with LED lighting loads. Universal dimmers have the ability to identify the type of load connected in the circuit to work with a magnetic or electronic transformer. Information on LED dimmer compatibility should be available from the supplier or manufacturer. An electrician may also be able to provide advice on selecting an LED lamp compatible with existing installed dimmers.

The demand for dimming of HID lamps is mainly directed to metal halide lamps. Attempting to dim metal halide lamps causes the arc-tube to operate at too low a temperature, which in turn results in the condensation of some of the metal halides. The consequence is a loss of colour from the condensed halides and the overall spectral output of the lamp is changed. The colour temperature changes (usually increases) and the colour rendering index falls significantly. For this reason, dimming of metal halide lamps is not recommended, as the colour and life performance of the lamps cannot be guaranteed.

5.2.4 Low Voltage Lighting Systems

12V halogen lighting systems use a transformer (either magnetic type or electronic type) to reduce the voltage from 240V to 12V. “Plug and play” 12V LEDs are available as direct replacements for 12V halogen lamps, however the LED lamp may in some cases not be compatible with the existing transformer (particularly electronic transformers) and thus not operate satisfactorily (does not illuminate or flickers). It may be necessary to test several LED lamp models to determine which is compatible with the existing transformer. Information on LED - transformer compatibility should be available from the supplier or manufacturer.

The alternative is to remove the transformer altogether and fit a 240V LED downlight kit.

5.2.5 Retrofit Linear LED Lamps

Replacing fluorescent tubes with linear LED tubes has become a common efficiency upgrade for fluorescent lighting systems. However, care needs to be taken to ensure that the upgraded installation is safe, and fit for purpose. It is therefore highly recommended that you check with the electrical safety regulator in your state, to ensure that any proposed retrofit of LED tubes into fluorescent luminaires complies with relevant safety regulations and standards.

5.2.6 Compatibility with control devices (basic circuits, power supply)

As the newer technologies have different control requirements, it is important to ensure that any replacement lamp is compatible with the control devices that are already present. For example:

- Fluorescent lamps are not designed to be operated directly from the mains supply as they require specific control gear to generate a high voltage to initiate the discharge and control the discharge current.
- Integral ballast compact fluorescent lamps should not be operated from other electronic switches, such as electronic timers and light sensors, as the electronics in the switches could be damaged.
- Mains voltage halogen lamps must be operated with a separate fuse in the system because the size of the lamp does not allow an effective fuse system to be built into the lamp.
- Low voltage lamps must never be operated directly off the mains supply, even through a phase control dimmer, as they are liable to explode. They should always be operated through an appropriately rated transformer or battery.

5.3 Energy Saving Calculations

At a simplistic level, the cost of running a light is directly related to the wattage of the globe plus any associated ballast or transformer. The higher the wattage, the higher the running cost and it is a straightforward calculation to work out the running cost of lamp over its lifetime:

Running cost = cost of electricity in $/kWh x wattage of lamp x lifetime in hours

Because the purchase price of more energy efficient lamps is currently higher than that of the normal incandescent lamps, it is also useful to consider the total lifetime cost of the replacement lamp. This demonstrates that although it costs more to buy the lamp, significant savings are still made over it lifetime as a result of the reduced energy use.

LEDs and CFLs are the cheapest form of household lighting when the life cycle cost is considered.
The type of lighting you choose will affect the amount of electricity used, your lighting bill, and greenhouse gas emissions.

As an example, the table below compares the cost to the user of a halogen lamp, CFL and LED lamp. It illustrates the large savings in electricity costs from using the CFL.

	Halogen	**CFL**	**LED**
Lamp Wattage	42	12	10
Quantity	1	1	1
Hours burned	10,000	10,000	10,000
Average life (hours)	2,000	6,000	10,000
Lumens	800	800	800
Electricity cost at $0.29 /kWh	$122	$35	$29
+ Lamp price	$3 x 5 lamps	$6 x 2 lamps	$10 x 1 lamp
= Total Costs	$137	$47	$39
Savings per lamp (vs. halogen)		$90	$98

5.3.1 Energy Efficiency Index

The Energy Efficiency Index (EEI), also known as the Energy Label, is a classification system for the lamp/ECG combination (it does not relate to luminaires). In Australia, all ballasts used with linear fluorescent lamp between 15 and 70W, are required to meet a Minimum Energy Performance Standard (MEPS) where the EEI = B2. Details of MEPS and EEI are contained in AS/NZS 4783.2: 2002, '*Performance of electrical lighting equipment - Ballasts for fluorescent lamps - Energy labelling and minimum energy performance standards requirements'*.

From 1 October 2004, linear fluorescent lamps manufactured in or imported into Australia must comply with Minimum Energy Performance (MEPS) requirements which are set out in AS/NZS 4782.2: 2004, '*Double-capped fluorescent lamps - Performance specifications - Minimum Energy Performance Standard (MEPS)*'.

The scope of linear fluorescent lamps MEPS covers FD and FDH lamps ranging from 550mm. The intention of MEPS is to improve end-use energy efficiency by eliminating lower efficiency fluorescent lamps from the market and to encourage the sale and purchase of higher efficiency fluorescent lamps.

The Minimum Energy Performance Standards (MEPS) for linear fluorescent lamps are set out as *minimum luminous efficacy* in *lumens per Watt* for various lamp sizes. There are also requirements for minimum *Colour Rendering Index and Mercury Content*. The methods for measurement of energy consumption are set out in AS/NZS 4782.1: 2004, '*Double-capped fluorescent lamps - Performance specifications - General (IEC 60081:2000, MOD)*' and AS/NZS 4782.3(Int): 2006, '*Double-capped fluorescent lamps - Performance specifications - Procedure for quantitative analysis of mercury present in fluorescent lamps*'.

The EEI classification systems, set out below with examples, are defined by certain limit values in lamp or system performance and range from A to G, with Class A being the best in terms of energy efficiency and Class G the worst.

Rating system for Household Lamps	**Rating system for Control component**.
A: Very Efficient	**A1:** Dimmable ECGs
B: >50 lm/W	**A2:** ECGs with low loss
C	**A3:** ECGs with higher losses
D: Mostly Halogen - > 16 lm/W	**B1:** Good low-loss control gear
E: Incandescent - GLS	**B2**: Poor low-loss control gear
F: Incandescent - < 10 lm/W	**C:** Conventional control gear
G: Least efficient - Coloured lamps	
(Calculated according to specified formula)	(Determined by test)

The standard, AS/NZS 4847.2(Int):2010, '*Self-ballasted lamps for general lighting services - Minimum Energy Performance Standards (MEPS) requirements'* specifies Minimum Energy Performance Standards (MEPS) requirements and related attributes for self-ballasted compact fluorescent lamps (CFLs) with integrated means for controlling starting and stable operation that are intended for domestic and similar general lighting purposes in Australia and New Zealand. It applies to self-ballasted lamps of all voltages and wattages irrespective of the type of lamp cap. It applies performance standards to the following attributes:

- Starting time
- Run-up time
- Efficacy
- Lumen maintenance
- Premature lamp failure
- Life
- Power factor
- Colour appearance
- CRI
- Mercury content
- Switching withstand
- Harmonics and immunity

6 Sustainability

As discussed in the introduction, sustainability is about sensibly and effectively using the resources currently available and thereby helping to ensure that the ability of future generations to meet their needs is not compromised.

6.1 Electricity

Electricity consumption during operation is by far the biggest issue relating to the sustainability of lighting systems. Lighting accounts for between 5 and 15% of residential energy use and up to 30% of commercial building energy use. It is estimated that the phase out of incandescent light bulbs, which commenced in 2009 in Australia (along with state based energy efficiency obligations schemes) is saving around 2.4 terawatt-hours (TWh) of electricity each year (equivalent to the total annual electricity consumption of 400,000 homes). The average household is estimated to be saving $70 per annum, with cumulative national savings of an estimated $5.5 billion.

On 20 April 2018, Council of Australian Governments (COAG) Energy Ministers agreed to further improve lighting energy efficiency regulation by phasing out inefficient halogen lamps in Australia and introducing minimum standards for LED lamps in Australia and New Zealand in line with European Union (EU) standards.

The phase out will remove remaining incandescent light bulbs and a range of halogen light bulbs from the Australian market, where an equivalent LED light bulb is available. This decision is expected to deliver around $1.4 billion in benefits to households and businesses, through savings on their electricity bills and reduced light bulb replacement costs.

Timing of the new regulation will align with revised EU minimum standards that will apply to LED light bulbs (planned for September 2021).

In addition to the obvious benefits in terms of reduction in energy use and production of greenhouse gases from the use of more energy efficient lamps, good lighting design that considers lighting zoning, lighting power densities, lighting ballasts, sub-metering, and lighting controls also contributes to overall sustainability. Conversely, poor lighting design can actually increase the energy consumption as users seek to improve their visual environment by using additional lighting and may increase the energy required to cool the building because of the higher level of heat generation.

6.2 Materials

6.2.1 Recyclability

Another consideration determining the sustainability of a product is whether it is possible to recycle its component parts (including the packaging).

There are already specialty recyclers who are able to the mercury, glass, phosphor and aluminium contained in lamps. The main driver for this is currently the concern over mercury contamination from mercury containing lamps (the recovered mercury is commonly sold to the dental industry, where it is used in amalgam for fillings).

Several states have household chemical collection programs and/or drop-off points that accept CFLs and fluorescent tubes for recycling. Other states are considering introducing similar schemes.

Several states have household chemical collection programs and/or drop-off points that accept CFLs and fluorescent tubes for recycling. Other states are considering introducing similar schemes. Detailed information about disposal and recycling, developed with the assistance of the states and territories is available at www.environment.gov.au/settlements/waste/lamp-mercury.html.

In an effort to reduce mercury emissions even further, the Australian Government, in conjunction with the Environment Protection and Heritage Council, has launched the *Fluoro-cycle* project in order to begin addressing this issue.

Fluoro-cycle (www.fluorocycle.org.au) is a voluntary partnership between the Australian Government and industry to increase recycling of mercury containing lamps by the commercial and public lighting sectors. These lamps currently account for approximately 90 per cent of all lighting waste.

Less mercury is released into the environment from the use of Compact Fluorescent Lamps (CFLs) than incandescent lamps despite the fact that CFLs contain a small amount of mercury. The reason for this is that burning coal to produce electricity also produces emissions of mercury. As CFLs use significantly less electricity than incandescent lamps, their use also results in lower overall emissions of mercury.

6.2.2 Embodied energy

Embodied energy is defined as the available energy that was used in the work of making a product. Minimising resource and energy usage, as well as waste (particularly hazardous waste) in the manufacturing and disposal of lighting equipment is also an important aspect of sustainability. However embodied energy in lighting equipment is generally insignificant compared to the energy used during the life of the equipment.

Selecting energy efficient lighting equipment is far more important than considering the embodied energy contained in the lighting equipment.

For example, CFLs are a more complex technology than traditional incandescent lamps, and so have a higher embodied energy, but this additional embodied energy will be offset many times over in the energy savings achieved from replacing an incandescent lamp with a CFL.

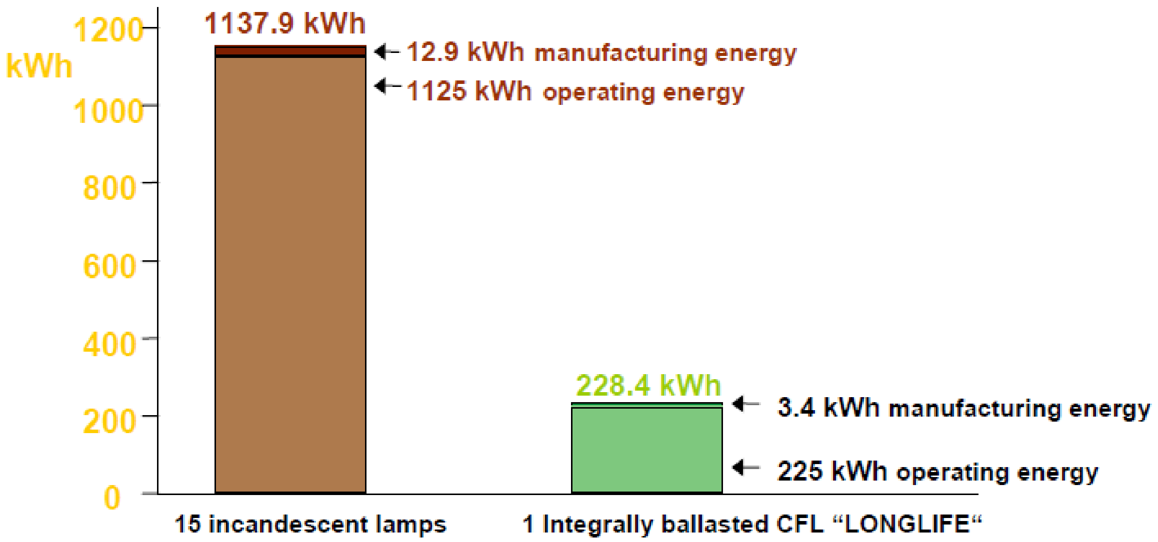


Figure 1 - Energy used in making and operating GLS Filament lamps and one CFL lamp - for same light over 15000 hours – does not include human energy in lamp replacements.

In this example we have a clear picture of the energy generated to make, and then operate two lamp types over an equal time period. If this energy is from fossil fuels, apart from the release of 'greenhouse effect' gases in related proportions, similar proportions of mercury are also released into the atmosphere. There is now only a small amount of mercury in all commonly used low-pressure gas discharge lamps and hence the threat from mercury pollution, via fossil fuel energy production associated with the incandescent lamp usage, is far greater than that imposed by many of the newer discharge lamps.

Different materials have a different embodied energy. Aluminium has a high embodied energy (170 MJ/kg as opposed to 12.7 MJ/kg in glass). Unless lamps of aluminium construction are required because of the environment in which the lamp will be operating, choosing one of plastic construction instead provides a more sustainable option.

6.2.3 LED Life-Cycle Assessment

The IEA-4E life-cycle assessment of LEDs[3] found that, when the environmental performance of an LED product life cycle were assessed, the "operational phase" was found to dominate the environmental impacts over the manufacturing and the end-of-life phases. On average, 85% of the environmental impact is linked to the operational phase, while the remaining 15% is shared mainly between manufacturing and end-of-life treatment. The environmental impact of the transport phase only accounts for 1% to 2%. Thus, the two most significant parameters contributing to the environmental impacts are luminous efficacy (lm/W) and useful life (hours of operation during lifetime).

Studies have found that the replacement of low efficacy lighting (e.g., the incandescent lamp, high-pressure mercury lamp) with high- efficiency, long-life LED-based lamps and luminaires brings a strong environmental benefit. However, lifetime of SSL products should be accurately and realistically specified, taking into account renovation rates and the potential for premature failure.

The IEA-4E study also found that, for residential lighting, incandescent and halogen lamps have much greater environmental impacts compared to an LED lamp. High quality compact fluorescent lamps (CFL) with lifespan of more than 12,000 hours and efficacy up to 65 lm/W has an impact comparable to good quality LED products (assuming the average lifespan of an integral LED lamp is 20,000 hours).

For commercial lighting, the T5 linear fluorescent lamp luminaire was the best- rated product in 2009. In studies published in 2013, the T5 lamp remains the product with the lowest environmental impacts, but thanks to the advances of LED technology, LED tubes are nearly at the same level of performance.
In the domain of outdoor lighting, the study found that the environmental impacts of LED street lighting luminaires are comparable with those of existing efficient, long-life technologies such as induction lamps with 100,000 hours average life. Common lighting technologies like high pressure sodium lamps and metal halide lamps have high efficacies (150 lm/W for sodium and 120 lm/W for metal halide) but relatively short lifespans (usually 12,000 to 24,000 hours). Compared to induction and LED technology in street lighting applications over a 100,000 hour period, the study found impacts were about 30% lower in global warming potential, respiratory effects and ecotoxicity compared to high pressure sodium and metal halide luminaires.

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[3] http://ssl.iea-4e.org/health-environment

7 Health consideration and lighting

As the phase-out of standard incandescent lamps and replacement with more energy efficient products progresses, questions have arisen over possible health issues. In particular, these concerns are associated with:

- Glare
- Flicker
- Ultraviolet emissions
- Blue light
- Mercury
- Electromagnetic fields
- Electromagnetic Compatibility and Safety

7.1 Glare

When high luminance LED components are visible by the users, glare can be a critical issue in LEDs. Glare does not constitute a risk in itself but it is a source of discomfort and reversible temporary visual disability that may be indirectly responsible for accidents and injuries. In indoor lighting, glare is assessed by the Unified Glare Rating (UGR) method. However, the UGR method is not applicable to point sources such as visible LEDs incorporated in a luminaire. Lighting manufacturers and designers should not perform UGR calculations on LED luminaires having visible LED point sources, as this approach can be misleading and yield low UGR values, thereby underestimating the physiological perceived glare. The use of the UGR method should be restricted to LED products with large diffusers, without any point sources.

The maximum luminance of the LED products is critical, whether they incorporate visible LED point sources or not. The luminance ratio between the light source and the background should be computed and adapted to each lighting installation according to visual ergonomics criteria.

7.2 Temporal Light Modulation[4]

Temporal Light Modulation (TLM) can affect people in terms of distraction, safety or health, including:

1. Visual perceptions: temporal light artefacts: flicker; stroboscopic effect; phantom array effect;
2. Cognitive and neurobehavioural: eye movement (saccade) disruption; visual performance; clerical work performance; brain activity; and
3. Health: epilepsy; headache and eyestrain; discomfort.

From a health point of view, a comprehensive risk analysis on this topic is provided in IEEE 1789-2015 (*IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers,* (chapter 7). This document summarises published negative health effects from temporal light modulation and provides decision trees to guide readers to understanding when TLM risks might be high. The report also identified areas in which knowledge gaps warrant further investigation.

However, some concern has been raised regarding the possible health implications associated with temporal light modulation. In particular for sufferers of:

- Photosensitive epilepsy
- Ménière's disease
- Migraines

[4] www.environment.gov.au/settlements/energyefficiency/lighting/faq-health.html#flicker

7.2.1 Photosensitive epilepsy

Photosensitive epilepsy is the name given to epilepsy in which all, or almost all, seizures are provoked by flashing or flickering light, or some shapes or patterns. Both natural and artificial light may trigger seizures. Photosensitive epilepsy is rare and only 5% of epileptics are diagnosed with this form of epilepsy.

Some known triggers for people with photosensitive epilepsy are:

- Watching television or playing video games
- Having a faulty lamp or television that flickers
- Strobe lights
- Driving at dawn or dusk with sun shining through a line of trees
- Sun flickering on water
- Looking out of the window from a fast moving vehicle
- Geometric patterns.

Although the frequency of flashing light most likely to trigger seizures varies from person to person, it is between 3 and 65 Hz (peak sensitivity 15 – 25 Hz) or flashes per second with modulation levels greater than 5%. CFLs and linear fluorescent lamps flicker at a rate well above this sensitivity range and do not pose a hazard to sufferers of photosensitive epilepsy. Similar so for the majority of LED lamps but some low quality lamps have been measured with light modulation in this frequency range.

Researchers have concluded that compact fluorescent lamps (CFLs) are no more likely to be a greater risk to people with photosensitive epilepsy than other lamps. The small number of cases of reactions to linear fluorescent tube flicker that have been recorded were almost certainly triggered by old technology which operated at a much lower frequency on a copper-iron magnetic controller, rather than an electronic controller which all modern fluorescent lamps use. Some LED lamps have been measured with light modulation at frequencies and levels similar to linear fluorescent tubes on a magnetic ballast so some precaution should be taken.

7.2.2 Ménière's disease

Ménière's disease afflicts about 0.2% of the population. It is a condition where excess fluid in the inner ear upsets the ear's balance and hearing mechanisms producing symptoms such as vertigo (dizziness), tinnitus (ringing in the ears) and hearing loss. The disorder usually affects only one ear and is a common cause of hearing loss.

There is no scientific evidence to suggest compact fluorescent lamps (CFLs) (or any fluorescent lights) can exacerbate or initiate symptoms of Ménière's disease. However, there are anecdotal reports that sufferers of Ménière's disease are more sensitive to flashing lights than others (because of their impaired balance systems), and so may be more susceptible to a phenomenon known as flicker vertigo (which can reportedly affect anyone).

Flicker vertigo may arise from flicker rates in the range of 4 to 30Hz or flashes per second. Symptoms range from vague and non-specific feelings of unease through to nausea, dizziness, migraines, unconsciousness, and even photosensitive epileptic seizures. Triggering events can be as simple as viewing fast moving objects, (such as fan, helicopter blades or a tree line from a moving car), that intermittently obscures the sun, creating a flickering effect.

CFLs and linear fluorescent lamps flicker at a rate well above that detectable by the human brain and so should not affect Meniere's sufferers. Some LED lamps have been measured with light modulation at frequencies and levels similar to linear fluorescent tubes on a magnetic ballast so some precaution should be taken.

7.2.3 Migraines

Migraine is one of the most common diseases of the nervous system. In developed countries migraine affects about 10-15% of people. Migraines can be triggered by many different things, including stress, exercise, certain foods, bright light, flickering light, loud noises, strong smells, lack of sleep or too much sleep. In women, attacks may be triggered by hormonal changes, for example during menstruation.

If light is suspected as the triggering event for migraines, ordinary headaches, or even eyestrain, the primary cause is likely to be glare, highly contrasting or inappropriate light levels. These problems are a result of poor lighting design rather than a feature of fluorescent lamps and can occur with any lighting technology if used inappropriately. Light fittings that enclose lamps and distribute light evenly without compromising light output and efficiency can help avoid these problems. Flicker has also been confirmed as a trigger but further research is required as it is currently unknown the specific range of conditions (frequency and modulation level) which cause the triggering of migraines.

Recommendations to mitigate the risk of migraine triggered by lighting include:

- Ensuring that lighting is adequate and well positioned
- Lighting should be properly maintained to minimise flicker
- Lamps should be fitted with the correct type of diffuser to minimise extreme brightness of the light generating source as much as possible
- Avoid reflected glare from shiny/polished surfaces, plain white walls etc., opt for matt finishes and break up surfaces with pictures, posters or plants
- Fit adjustable blinds to windows.

While light sources with a detectable flicker can trigger migraines in susceptible individuals, CFLs, linear fluorescent s and a range of LED lamps flicker at a rate well above that detectable by the human brain and so should not affect migraine sufferers. Some LED lamps have been measured with light modulation at frequencies and levels similar to linear fluorescent tubes on a magnetic ballast so some precaution should be taken.

7.3 Ultraviolet emissions

As mentioned in previous sections, ultraviolet radiation occurs naturally from the sun, sitting just beyond the violet end of the visible range of the electromagnetic spectrum.

Ultraviolet radiation is categorised into three bands - UVA, UVB and UVC:

Name	Description	Wavelength
UVA	Long wave ultraviolet	400 to 320nm
UVB	Medium wavelength ultraviolet	320 to 280nm
UVC	Short wavelength ultra violet	280 to 100nm

Exposure to UV can have beneficial effects. A small amount of radiation is essential to the body as it stimulates the production of vitamin D, which plays a crucial role in food absorption, skeletal development, immune function and blood cell formation. However, only 5 to 15 minutes of casual sun exposure of hands, face and arms two to three times a week during the summer months is necessary to keep your vitamin D levels high[5].

On the other hand, too much solar ultraviolet exposure (especially at shorter wavelengths) can be very damaging to skin and eyes. It is well-known that it is responsible for skin cancer - which has dramatically

[5] World Health Organisation

increased over the last two decades with more people enjoying both holiday sunbathing and the use of sun beds.

UV radiation also has the effect of colour bleaching (e.g. the fading of coloured curtains by sunny windows).

The “photobiological safety” of lamps, luminaires and lighting modules has been internationally addressed by the Commission Internationale de l’Eclairage (CIE), the Illuminating Engineering Society of North America (IESNA) and the International Electrotechnical Committee (IEC) through close collaborations and joint working groups. They led to the following standards describing the photobiological safety of lamps and lamp systems: Joint publication CIE S009 [CIE 2006] and IEC 62471:2006 [IEC 2006], IESNA/ANSI RP- 27 series [IESNA 2000, 2005, 2007]. These documents are not identical but similar in content.

7.3.1 Artificial light sources

Ultraviolet radiation is produced to various degrees by all artificial light sources. The common household lamps such as incandescents, halogens, LEDs and CFLs all produce some UV.

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) conducted a study[6] into a range of CFLs, incandescent lamps and halogen lamps. Of the tested lamps, those with the highest UV levels, measured at a distance of 10cm over a period of 8 hours was equivalent to spending approximately 6 minutes in the midday summer sunshine in Brisbane and 7 minutes in Melbourne.

The study found that UV emissions from all lamps decreased rapidly with distance. If people are concerned about UV exposure they should minimise the time spent closer than 25cm from these lamps or use 'double envelope' or 'covered' LED or CFLs (these types of lamps look similar to 'pearl' incandescents).

7.3.1.1 LED Light Sources

The vast majority of white LEDs rely on a chip emitting blue light, which then excites a layer of phosphors to produce white light. As a consequence, the emission spectrum of a white LED consists of a narrow blue primary peak and a large secondary peak in the yellow- orange- red region. The two peaks are separated by a region of low emission in the blue- green part of the spectrum. In many cases, the blue peak lies in the spectral region corresponding to the highest retinal phototoxicity.

However, since UV radiation is mainly absorbed by the cornea and the lens, excessive exposures lead to photokeratitis, photoconjectivitis, and cataracts. Infrared radiation with wavelengths greater than about 1.4 μm are mainly absorbed by the cornea and may induce corneal burns. Emitting negligible amounts of UV and IR radiation, LEDs should not be expected to contribute to the apparition of photokeratitises, photoconjectivitis and cataracts.

Emitting UV light can have deleterious effects on skin, such as burning and aging, and can cause cancer if exposure is prolonged. With visible and infrared radiation, burns can be induced with very high irradiances. LEDs used for lighting are currently far from reaching the high irradiance levels required to burn the skin. Therefore, the general population should not be concerned by potential risks to the skin arising from the use of LEDs in lighting. As it is the case with the very small amount of UV radiation emitted by CFLs, only a small number of people suffering from photosensitive syndromes might see an aggravation of their pre- existing condition triggered by blue light emitted by LEDs. Patients taking photosensitizing drugs should also be aware of a potential risk.

[6] www.arpansa.gov.au/radiationprotection/factsheets/is_CFL.cfm

7.3.1.2 Fluorescent lamps

Fluorescent lamps, by the nature of their operation, give out low levels of UV. The amount is quite small and does not pose a health hazard to people who are exposed to it. The amount of UV given out by fluorescent tubes in a typically lit office is only a small proportion of that in average daylight. While some CFLs do emit slightly more UV light than equivalent incandescent light bulbs, these emissions are not significant if the CFLs are installed more than 25cm away from people, such as in ceiling fittings.

7.3.1.3 High intensity discharge lamps

High and low pressure sodium lamps produce small amounts of UV which is virtually all absorbed by the outer glass bulbs. They are not classed as being of any serious concern as regards UV radiation.

High pressure mercury and metal halide on the other hand, does produce relatively high levels of UV from their arc-tubes. Those versions with glass outer bulbs have the UV significantly reduced by the filtering effect of the glass and do not pose any health hazard. They can, however, produce a bleaching effect on colour sensitive materials over long periods of exposure.

Metal halide lamps with quartz outer bulbs produce levels of UV that could be a health hazard, because normal quartz does not filter out UV radiation. It was always necessary to use UV filters on light fittings with these lamps. However, most manufacturers now use special ‘UV filter’ quartz, for their range of metal halide lamps. From a health point of view, these can be used without the need for additional UV filters on light fittings. However, it may still be prudent to use UV filters on the light fittings to eliminate the effect of bleaching if the illuminated objects are particularly sensitive (e.g. valuable paintings).

7.3.1.4 Halogen lamps

The quartz envelope used for halogen lamps allows the transmission of ultraviolet electromagnetic waves in addition to the visible spectrum. Therefore lamp manufactures now offer a range of tungsten halogen lamps that use a ‘doped’ material that effectively cuts off the ultraviolet radiation. These ultraviolet absorbing chemicals are usually added during the molten phase of manufacture.

7.3.2 Light sensitivity conditions[7]

With the increased use of LEDs and compact fluorescent lamps (CFLs), some concern has been raised that these lamps can have an adverse impact on the health of individuals who are affected by ultraviolet (UV) light, specifically sufferers of Systemic Lupus Erythematosus (SLE) or Lupus.

Lupus, in its many forms, is an autoimmune disorder characterised by chronic inflammation of body tissues. People with Lupus produce antibodies that target their own healthy tissues and organs. The cause of Lupus is not clear but genetics, viruses, UV light, and medication all appear to play some role. Lupus is up to eight times more common in women than men. Exacerbations or flare ups of Lupus can be induced by exposure to any source of UV emissions including sunlight.

There can be a great deal of variation in the UV output of different bulbs, even within the same class (i.e. incandescents, halogens and CFLs). The slightly elevated levels of UV produced by CFLs may pose a problem for sensitive sufferers of Lupus, if not ameliorated. For example, there are rare instances recorded of prolonged exposure to bare linear (tubular) fluorescent lamps provoking Lupus in hypersensitive individuals.

Some double envelope CFLs - designed to have a similar appearance to traditional incandescent lamps - emit lower UV than the single envelope CFLs – however, this not always the case with all models.

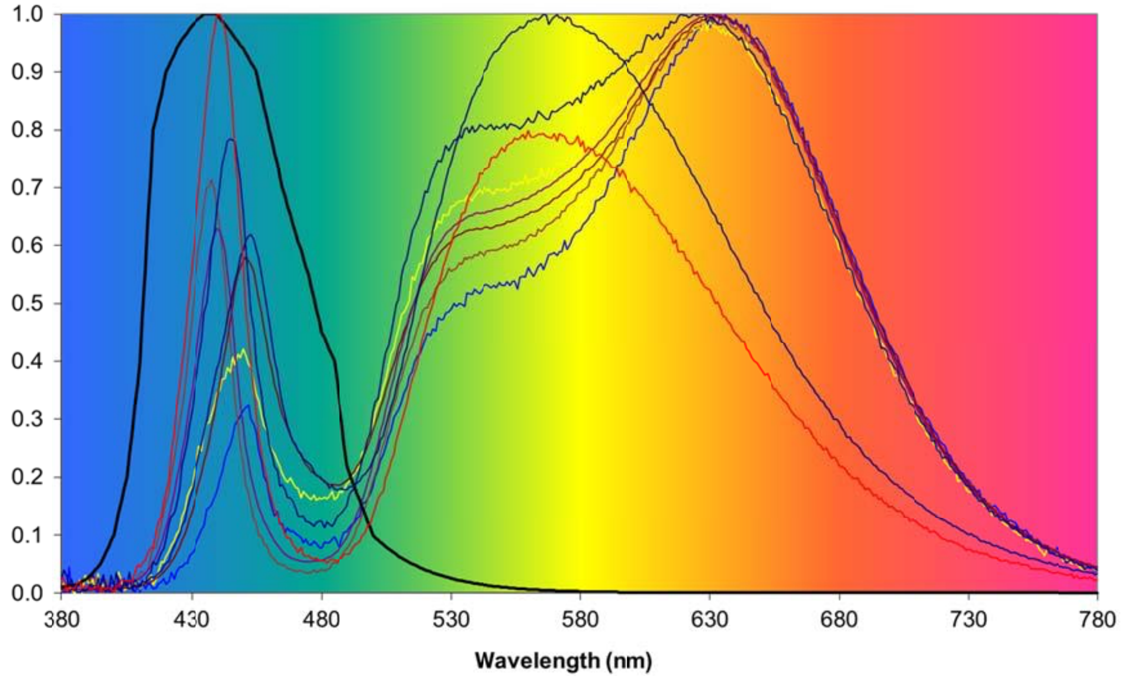
[7] www.environment.gov.au/settlements/energyefficiency/lighting/faq-health.html

Traditionally, light covers, light fittings and light diffusers have been used in homes for both aesthetic reasons and to reduce glare from bare light bulbs. If used correctly acrylic light covers can also reduce UV light levels by as much as 94 per cent. Available in a range of styles, light covers should be positioned between the light source (light bulb) and yourself to reduce the level of UV light. It is important that you cannot see the light bulb once the cover is fitted.

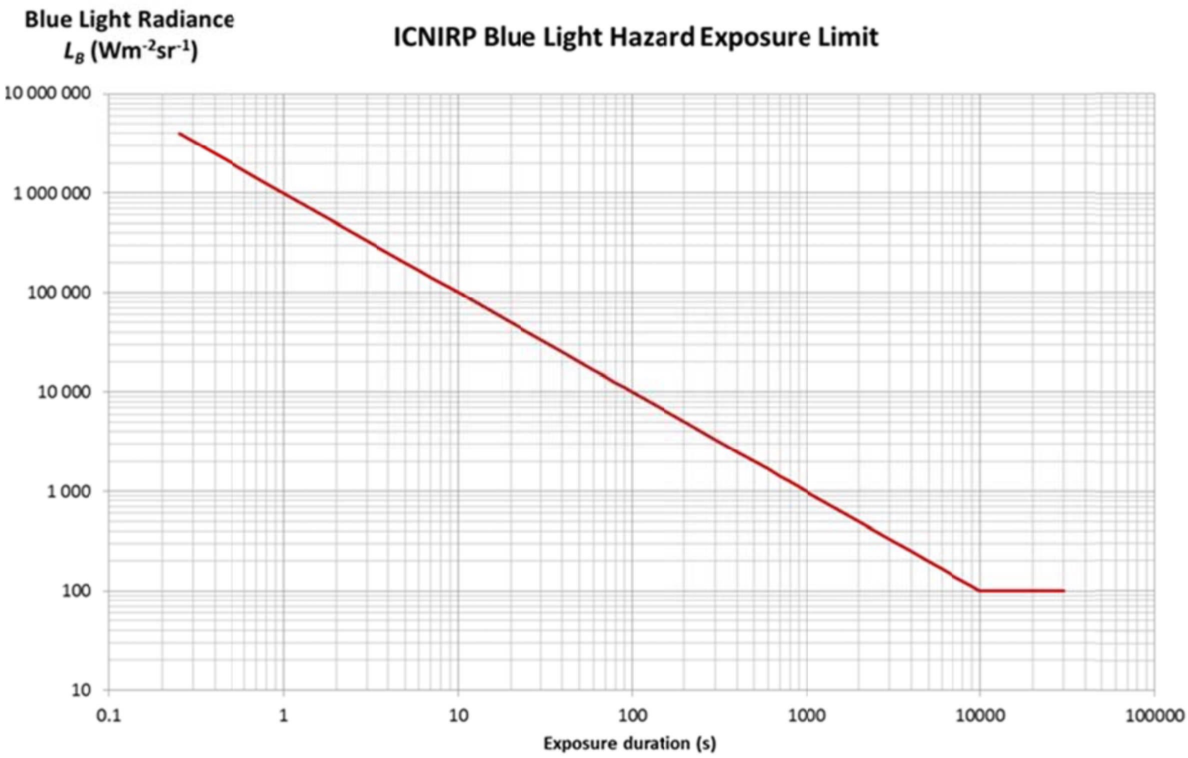
7.4 Blue Light

7.4.1 Retinal Damage

A key feature of LEDs that has attracted the attention of lighting specialists and ophthalmologists is blue light. The majority of LEDs producing white light rely on a chip emitting blue light which then excites layers of phosphors to produce light using fluorescence. As a result, the emission spectrum of a white LED consists of a narrow blue primary peak and a large secondary peak in the yellow-orange-red region. The two peaks are separated by a region of low emission in the blue-green part of the spectrum. In many cases, the blue peak lies in the spectral region corresponding to a high risk of retinal damage. This can be seen in the figure below, with the black curve indicating the blue light hazard zone (retinal sensitivity to blue light damage) and the coloured lines representing the spectral outputs of various LED products.



The figure below shows the blue light exposure limit expressed in terms of blue light radiance, published by the International Commission for Non- Ionizing Radiation Protection (ICNIRP).



Generally speaking, most LEDs used for general purpose illumination do not pose a significant blue light hazard to the general population. However the IEA-4E Solid State Lighting Annex recommends that employers should assess that workers are not exposed to levels in excess of generally accepted exposure limit values. Employers can demonstrate this by using several means: generic assessments, theoretical assessments or measurements, and there are a number of standards published to assist with this. Certain categories of workers (lighting engineers, stage artists, etc.) can be exposed to high doses of artificial radiation emitted by LEDs during their daily activities. Since the damage mechanisms are not yet fully understood, exposed workers should use appropriate individual means of protection as a precautionary measure (e.g. glasses filtering out blue and violet light).

7.4.2 Circadian Rhythm Issues

Light has a strong influence on the regulation of circadian rhythms, which control sleep/wake patterns in humans. This influence has been observed by chronobiologists in human subjects (including some blind subjects) and many other animal species since the 1980s. Light is the most powerful agent to perform the daily synchronization of the biological circadian clock. In the absence of light stimuli, the circadian clock would drift and become desynchronized with the daily schedule.

The eye's intrinsically photoreceptive retinal ganglion cells (ipRGCs) are directly connected to the suprachiasmatic nucleus (SCN), a tiny region of the brain located in the hypothalamus. The SCN is responsible for controlling circadian rhythms. It has been demonstrated that the excitation of ipRGCs with light is responsible for suppressing the production of melatonin (a "sleep" hormone). It is also responsible for many other non- visual effects (pupil constriction, increase of the heart rate and body temperature, stimulation of cortisol production (a "wake up" hormone)), etc. The ipRGCs have a spectral sensitivity which was found to be maximal at a wavelength of about 480nm (blue-green).

Thus, it is thought that exposure to blue-green light can suppress sleep, and in response lighting colour choices should be made, regardless of the lighting technology used, that are sensitive to circadian rhythms.

7.5 Mercury

Mercury is a naturally occurring element and a potent neurotoxin. Emissions in the air can come from both natural and man-made sources. Coal-fired power plants are the largest man-made source because mercury that naturally exists in coal is released into the air when coal is burned to make electricity.

As has been discussed in earlier sections, a variety of lamp types require mercury to operate. Generally the higher the power usage the more mercury is required in the operation of the lamp. Mercury containing lamps include:

- High pressure discharge (HID) lamps such as mercury vapour lamps, which typically contain about 30 milligrams (mg) of mercury, as used for street and road lighting
- Linear fluorescent tubes, as used in most commercial and public buildings
- Compact fluorescent lamps (CFLs), mostly used in homes.

On 1 June 2017, requirements for maximum mercury content were reduced for linear fluorescent lamps and compact fluorescent lamps in Australia, in order to meet the requirements of the Minamata Mercury Convention and align with levels set by major markets. Changes are reflected in the GEMS (Double-capped Fluorescent Lamps) Determination 2017[8] and the GEMS (Self-ballasted Compact Fluorescent Lamps for General Lighting Services) Determination 2017[9] and came into force on 1 December 2017:

- CFLs less than 30W:
  - the amount of mercury contained in the product must not exceed 2.5 mg.
- CFLs 30W and over:
  - The previous maximum mercury content of 5 mg in CFLs remains unchanged.
- Linear fluorescent lamps (triphosphor <60W):
  - The maximum mercury content of 15 mg has been decreased to meet the Minamata Convention on Mercury - specified maximum level of 5 mg.

As the number of CFLs in use increases so has awareness of the hazards and health impacts associated with exposure to the element, leading to questions about whether they are safe to use. However, the amount of mercury in domestic lamps is very small (in many cases, less than the mandatory 5mg), roughly equivalent in size to the tip of a ballpoint pen, and it is sealed within the CFL glass tubing. By comparison, there is up to five times that amount of mercury in a watch battery; between 60 to 200 times that in a single 'silver' dental filling in people's mouths; 100 to 200 times that amount in the old-style thermometers many people still have in their medicine cabinets; 200 times that amount per switch in the light switches of certain freezers; and about 500 times that amount in thermostats on the walls of people's homes.

The mercury contained in CFLs and these household products pose no threat during use, unless the device is broken. Therefore, these products should always be handled carefully and properly disposed.

In addition, CFLs use around one-quarter the energy of incandescent lamps, so they last longer, require less electricity, and avoid some of the mercury emissions from coal-fired power plants.

7.5.1 Disposal

CFLs can generally be disposed of in regular garbage bins - where the garbage goes to landfill. However, it is best to check with the local authority who manages garbage collection, as different local authorities may have different arrangements. If disposing of CFLs this way, it is best to wrap them in newspaper to prevent them from breaking.

[8] https://www.legislation.gov.au/Details/F2017L00652
[9] https://www.legislation.gov.au/Details/F2017L00653

Where possible, it is preferable to have them recycled by specialty recyclers. Recycling can safely recover and reuse the mercury, glass, phosphor and aluminium. The recovered mercury is commonly sold to the dental industry, where it is used in amalgam for fillings. Most lamp recyclers will collect large quantities of lamps from capital cities and selected regional areas and several states have household chemical collection programs or drop-off points that accept CFLs for recycling. Other states are considering introducing similar schemes. Detailed information about disposal and recycling, developed with the assistance of the states and territories is available at www.environment.gov.au/settlements/waste/lamp-mercury.html.

FluoroCycle (www.fluorocycle.org.au) is a voluntary Australian scheme that aims to increase recycling of mercury-containing lamps from the commercial and public space lighting sectors. Those sectors account for the largest consumption of mercury-containing lamps.

Interwaste in New Zealand offers a zero-to-landfill 100% recycling service for all forms of mercury-containing lamps. Refer http://www.interwaste.co.nz/services/advanced-recycling.

CFLs should not be placed in kerbside recycling collections because they can break during transport and contaminate recyclable items. Rubbish dumps do not have the facilities to recycle fluorescent lamps.

7.5.2 Breakages

The short term nature of the potential exposure (particularly after effective clean-up of broken CFL material) does not constitute a significant health risk to exposed adults (including pregnant women) or children. However, following these simple and straightforward clean up and disposal instructions as a cautionary approach, will further reduce risk:

- Open nearby windows and doors to allow the room to ventilate for 15 minutes before cleaning up the broken lamp. Do not leave air conditioning or heating equipment on, as this could re-circulate mercury vapours back into the room.
- Do not use a vacuum cleaner or broom on hard surfaces because this can spread the contents of the lamp and contaminate the cleaner. Instead scoop up broken material (e.g. using stiff paper or cardboard), if possible into a glass container which can be sealed with a metal lid.
- Use disposable rubber gloves rather than bare hands.
- Use a disposable brush to carefully sweep up the pieces.
- Use sticky tape and/or a damp cloth to wipe up any remaining glass fragments and/or powders.
- On carpets or fabrics, carefully remove as much glass and/or powdered material using a scoop and sticky tape; if vacuuming of the surface is needed to remove residual material, ensure that the vacuum bag is discarded or the canister is wiped thoroughly clean.
- Dispose of clean up equipment (i.e. gloves, brush, damp paper) and sealed containers containing pieces of the broken lamp in your outside rubbish bin - never in your recycling bin.
- While not all of the recommended clean-up and disposal equipment described above may be available (particularly a suitably sealed glass container), it is important to emphasise that the transfer of the broken CFL and clean-up materials to an outside rubbish bin (preferably sealed) as soon as possible is the most effective way of reducing potential contamination of the indoor environment.

7.6 Electromagnetic fields

CFLs and LEDs, like all lamps and electrical appliances, will produce 50 Hz magnetic fields from the currents drawn from the supply. Both the lamp and the associated household wiring will produce these fields. The magnetic fields from the wiring should theoretically be lower with LEDs and CFLs than incandescent globes because of their lower power consumption. Magnetic fields from the lamps themselves may be higher than from incandescent lamps very close to the fittings but preliminary tests undertaken on a small range of CFLs tested at the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) did not find any cases where the 50 Hz magnetic fields, at distances greater than 30 cm, were elevated above typical residential levels.

The high frequency electrical currents produced within the base of the lamp will cause some localised electric and magnetic fields. The radiofrequency emissions are constrained by the need to avoid producing electrical interference to well below the limits known to be associated with any health effects.

Normally electromagnetic interference isn't a significant issue, especially if lamps comply with the relevant electromagnetic compatibility (EMC) standards and appropriate installation procedures are followed. In the rare instances, where problems do occur consult the lamp ballast and/or the control gear supplier.

The key international standards related to electromagnetic compatibility are:

- IEC 61000*, 'Electromagnetic compatibility (EMC)'*
- IEC 61547*, 'Equipment for general lighting purposes – EMC immunity requirements'*

7.7 Electromagnetic Compatibility and Safety Requirements

The Regulatory Compliance Mark (RCM) (see figure below) is a symbol signifying that a supplier has taken the necessary steps to have the product comply with the electrical safety and/or electromagnetic compatibility (EMC) legislative requirements. It's intended as an easy way for consumers to identify products which have met certain electrical standards.

The electrical safety requirements are set out in various Acts and Regulations of each Australian State and Territories and New Zealand and administered by the various electrical safety regulators. EMC is a Federal requirement administered by the Australian Communications and Media Authority (ACMA) and the New Zealand Ministry of Economic Development. Whilst EMC is mandatory in all states, note that only some States in Australia, the use of the RCM mark has become mandatory for electrical compliance.

The RCM is a common mark that is accepted by the ACMA and all of the electrical safety regulators to simplify marking requirements and provide an easily recognized as a conformity mark.
The electrical safety requirements for using the mark are set out in the Australian Standard AS/NZS 4417. Use of the mark is allowed as proof of compliance based on a Certificate of Approval, provided all other conditions of the mark as spelt out in AS/NZS 4417 are followed. This includes registration of each importer, known as the Responsible Supplier on the database, as well as registration of any level 3 class products, as set out in AS/NZS 4417.2.

8 Lighting Control Systems

Lighting control systems form an important part of efficient lighting. Once efficient luminaires and lamps have been chosen, and incorporated into an efficient lighting design, the final efficiency aspect to be considered is controlling the lights in an efficient manner - to ensure they are only switched on as and when required. There are several types of lighting control systems, and these can be employed in combination - often these types of controls are integrated into a building management system (BMS) which provides a central point for programming the operation of the lighting system.

Simple timers use either chronological time (the time of day) or astronomical time (the time of sunrise and sunset) to control when the lights are turned on and off. This is the simplest for of lighting control, yet is very effective for ensuring that lights are not left on overnight or at weekends when a building is not in use.

Occupancy sensors can be used to ensure that lights are only turned on when occupants are present. These will provide greater energy savings than simple timers. Various types of motion detectors are typically used to sense occupancy:

- Passive infrared (PIR) sensor, which works on “heat movement” detection. Inside of device is a pyroelectric sensor calibrated to detect infrared radiation radiated by human body movement. Based on the detection, the sensor operates the lighting load connected to it.
- Ultrasonic sensor, similar to radar, works on the Doppler shift principle. An ultrasonic sensor will send high frequency sound waves in area and will check for their reflected patterns. If the reflected pattern is changing continuously then it assumes that there is occupancy and the lighting load connected is turned on. If the reflected pattern is the same for a preset time then the sensor assumes there is no occupancy and the load is switched off.
- Microwave sensor - similar to the ultrasonic sensor, a microwave sensor also works on the Doppler shift principle. A microwave sensor will send high frequency microwaves in an area and will check for their reflected patterns. If the reflected pattern is changing continuously then it assumes that there is occupancy and the lighting load connected is turned on. If the reflected pattern is the same for a preset time then the sensor assumes there is no occupancy and the load is switched off. A microwave sensor has high sensitivity as well as detection range compared to other types of sensors.

Daylight detection utilises photocell sensors to ensure that lights are turned off, or dimmed, when there is sufficient sunlight. These can be used very effectively in combination with daylight harvesting.

More recently LED smart lighting has become available on the market that may be controlled via smart phone apps, supplier remote controls or smart household systems. This is discussed further in Chapter 10.

Experience has shown that all these systems are sensitive to appropriate design and careful commissioning. They must be designed to work well with the building occupants, and well commissioned to ensure that they operate as intended.

9 Myths and Tips

This section busts some of the public myths and misconceptions regarding lighting, and gives some useful tips to consider when designing or specifying lighting installations.

Not all LEDs are efficient

LEDs are an emerging technology and are often claimed to be very efficient. In practice, products that use LEDs have a range of efficacies, thus great care should be taken when selecting LEDs for any lighting purpose.

Not all smart lamps are smart

Smart LED lamps, or more commonly simply “smart lamps”, are appearing more and more in today’s lighting market[10]. These lamps are connected to a communications network, typically using a wireless technology. They can offer significant energy savings, such as the ability to turn off lights when occupants leave the house. However, energy efficiency gains from households switching to LED technology may be compromised by the standby power consumption of these lamps, which require energy even when not providing light, in order to keep the network connection alive.

Fluorescent lighting DOES NOT requires a large amount of energy to start

There is a very common myth that fluorescent lights should not be switched off, as they require more energy to start than can be saved by turning them off. This is not the case. Fluorescent lights may use up to 300% more power to start, but this is only for around 3 milliseconds.

Low voltage DOES NOT mean energy efficient

There is a common misconception that low voltage incandescent lamps are also energy efficient. This is misleading. Due to the fact that their filament runs at higher current and therefore hotter, low voltage lamps are slightly more efficient than mains voltage incandescent lamps. However, they do require a transformer which has a power loss (particularly magnetic transformers).

Thus a standard 12 volt 50 watt halogen downlight with an iron core transformer uses 50 watts for the lamp and up to 15 watts for the transformer = 65 watts per fixture.

Low voltage halogen reflector lamps (dichroic lamps) are often inappropriately used for lighting of large spaces. These lamps are essentially spot lights - they emit light in a narrow beam. This means that many lamps are required to light a large space. Examples have been found where a room that would have traditionally been lit with one or two GLS lamps or CFLs are now lit with 12 or more dichroics.

To replace 50W low voltage lamps, there are now 30W and 35W IRC versions which have equivalent light output. When combined with electronic transformers, these can result in significant energy savings.

Thus a standard 12 volt 35 watt IRC halogen downlight with an electronic transformer uses 35 watts for the lamp and around 3 watts for the transformer = 38 watts per fixture.

However, fluorescent lighting represents the most efficient solution for general purpose illumination.

[10] http://ssl.iea-4e.org/product-performance/new-product-features/standby-of-smart-lamps-first-report

Incandescent lamps and fire risk

New wiring regulations have set tight restrictions on the clearances from flammable materials when installing halogen and incandescent lamps for reasons of fire risk.

Downlights and insulation

Downlights require multiple holes in the ceiling and the insulation above it, thus reducing ceiling insulation performance.

CFL colour temperature

CFLs are available in a wide range of colour temperatures, from warm white (suitable for homes) through to daylight colours which are more suited to commercial applications.

CFLs and mercury

CFLs contain a small amount of mercury. However, less mercury is released into the environment from the use of CFLs than from the use of inefficient incandescent lamps. This is because burning coal to produce electricity releases mercury into the environment. The new minimum energy performance standards (MEPS) for CFLs includes a maximum mercury level of 5mg per lamp.

CFLs and LEDs on dimmers and other control circuits

Certain CFLs and LEDs are not compatible with certain dimmers, movement sensors, sunset switches, touch lamps and other such circuits. Refer to manufacturer's specification for circuit compatibility.

Residential lighting controls

"Smart house" cabling and related systems can make use of sensors and smart controls to improve lighting efficiency in homes.

10 The Future of Lighting

This chapter examines some of the emerging technologies that are finding their way to the marketplace. The future for these technologies is unclear, however they represent an interesting “watch this space” for how lighting technologies might evolve.

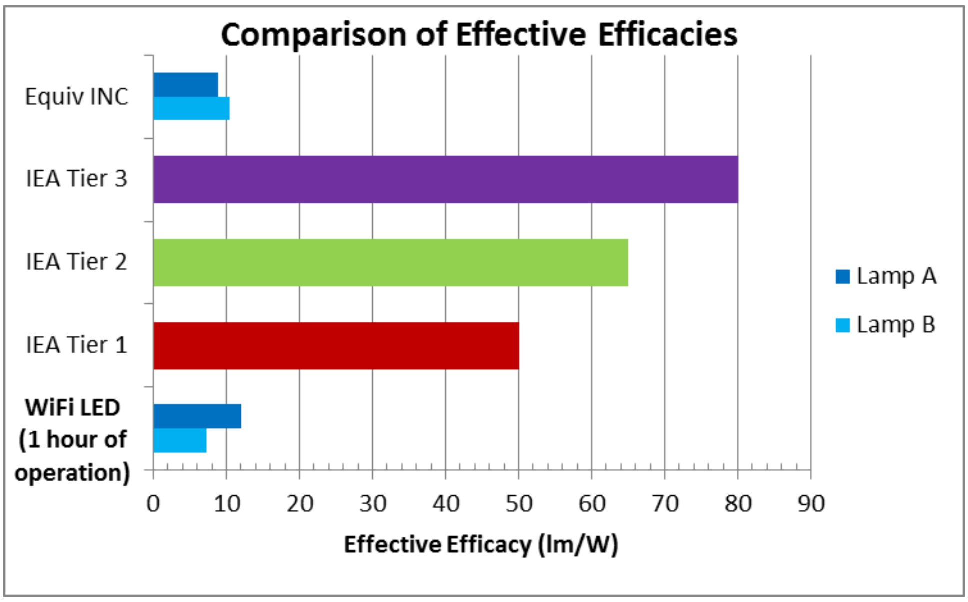
10.1 Smart Lighting

10.1.1 Smart Lamps

Smart LED lamps, or more commonly simply “smart lamps”, are appearing more and more in today’s lighting market[11]. These lamps are connected to a communications network, typically using a wireless technology such as WiFi, Bluetooth, Zigbee, etc. They offer a range of features, such as remote operation and dimming, the ability to tune colour, etc. They can offer significant energy savings, such as the ability to turn off lights when occupants leave the house.

However, energy efficiency gains from households switching to LED technology may be compromised by the standby power consumption of these lamps, which require energy even when not providing light, in order to keep the network connection alive.

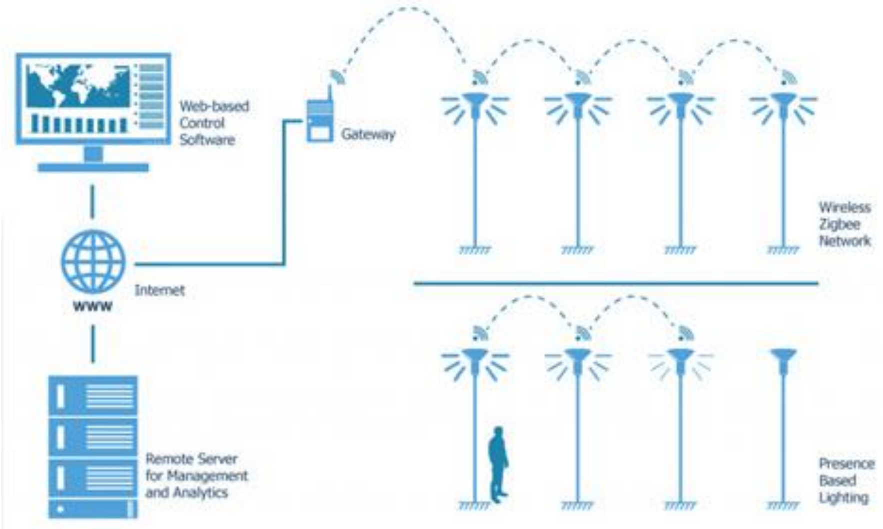
The longer the daily use of a lamp, the less significant the standby mode power consumption is relative to the power consumed when ON, however the average residential time of use (i.e. when turned ON) for lamps in Australia and New Zealand is only 1–2 hours. The figure below compares the measured efficacy (lumens per Watt) of the tested lamps to similar incandescent lamps and the IEA 4ESSL recommended LED efficacy levels. This figure shows the “effective efficacy” of two smart lamps, when the standby energy consumption is taken into account (lamps run 1 hour per day). As can be seen in this figure, the smart lamps’ effective efficacy can be around the same as an incandescent, once standby energy is taken into account. Thus care needs to be taken when selecting a smart lamp, to ensure that standby energy use is also examined.



[11] http://ssl.iea-4e.org/product-performance/new-product-features/standby-of-smart-lamps-first-report

10.2 Smart Luminaires

Smart luminaires are able to communicate. When combined with motion detection, intelligent sensors and processing capability, smart luminaires have the ability to operate in a more efficient manner. For example, outdoor lights that can determine the direction of a pedestrian or vehicle travel, and command other lights to turn on (and off) in anticipation of the arrival of the pedestrian or vehicle. This is illustrated in the figure below. Such systems are also available for commercial and industrial lighting.



10.3 "Li-Fi"

Light Fidelity (Li-Fi) is a bidirectional, high-speed and fully networked wireless communication technology similar to Wi-Fi. It uses visible (or infrared and near-ultraviolet) light to transmit data at very high data rates. This is achieved by modulating the LED light source at very high frequencies, and encoding data within this modulation (which is not visible to the human eye). The signal is then detected by a photo-detector, for example within a mobile phone. They key advantage of this is the very high data transmission rates that are achievable.

Although Li-Fi LEDs would have to be kept on to transmit data, they could be dimmed to below human visibility while still emitting enough light to carry data. The light waves cannot penetrate walls which makes a much shorter range, though more secure from hacking. Direct line of sight is not necessary for Li-Fi to transmit a signal - light reflected off walls can be used.

10.4 Power Over Ethernet

It is becoming more common for commercial luminaires to be powered from an Ethernet cable, rather than from a mains power cable. Dimmable luminaires, such as those using DALI control, will often utilise an Ethernet connection, and with power over Ethernet this connection can be used to both power the luminaire and control it. This has only become possible with the reduction in luminaire power afforded by LEDs. Connected luminaires can be detected by the power source, and the device can then negotiate the amount of power required or available to it. Up to 25.5 W is available for each device.

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Osram - Product Training Programme

Philips - Lighting Academy

Queensland University of Technology - In-House Training Modules

Your Home – Lighting Design Guide - www.yourhome.gov.au

Glossary and Abbreviations

A: amps

AC: alternating current

ACMA: Australian Communications and Media Authority

Ballast: a component of conventional control gear. It controls the current through the lamp, and is used with discharge lighting, including fluorescent and high intensity discharge lamps. The term is sometimes used loosely to mean control gear. Also called a choke.

BCA: Building Code of Australia (now National Construction Code or NCC)

BLF: ballast lumen factor = ratio of the light output of the reference lamp operated with the test ballast, to the light output of the reference lamp operated with the reference ballast

cd: Candela = luminous intensity = power emitted by a light source in a particular direction

CFL: compact fluorescent lamp

CFLi: compact fluorescent lamp with integrated ballast

CFLn: compact fluorescent lamp with non-integrated ballast

Colour rendering: an indicator of how accurately colours can be distinguished under different light sources. The colour rendering index (CRI) compares the ability of different lights to render colours accurately with the measurement of 100 considered to be excellent. A value of 80 and above is good and appropriate for most situations where people are present. Where colour identification is important, a value of 90 or above should be used. The colour rendering index (CRI) has been used to compare lamps for over 40 years but the CIE does not recommend its use with white light LEDs. CIE Technical Report 177:2007 concludes that “the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set”. The CIE are currently investigating this issue in two technical committees. It should be recognised that this is a highly contentious area.

CRI: colour rendering index

Colour temperature: also known as colour appearance, the colour temperature is the colour of ‘white’ the light appears. It is measured in Kelvin (K), and ranges from 1800K (very warm, amber) to 8000K (cool). 6500K is daylight. There are many colours of ‘white’ available. For general use these are: warm white (2700–3300K), cool white (3300–5300K) and cool daylight (5300–6500K).

Control gear: a ‘package’ of electrical or electronic components including ballast, power factor correction capacitor and starter. High-frequency electronic control gear may include other components to allow dimming etc.

DC: direct current

Diffuser: a translucent screen used to shield a light source and at the same time soften the light output and distribute it evenly.

Discharge lamp: a lamp which produces illumination via electric discharge through a gas, a metal vapour or a mixture of gases and vapours.

Duv: distance from Planckian locus

EEI: ballast energy efficiency index

Efficacy (luminous efficacy): the ratio of light emitted by a lamp to the power consumed by it, that is, lumens per Watt. When the control gear losses are included, it is expressed as lumens per circuit Watt. The higher the efficacy the more efficient the product.

ELV: extra low voltage, typically not exceeding 50 V AC

EMC: electromagnetic compatibility

GLS: general lighting service lamp

Halogen: filament lamp utilising halogen gas fill

HID: high intensity discharge lamp

HPS: high pressure sodium lamp

IES or IESANZ: Illuminating Engineering Society of Australia and New Zealand

Illuminance: the amount of light falling on an area, measured in lux. 1 lux is equal to one lumen per square metre. The higher the Lux, the more visible light on a surface area.

Incandescent: filament lamp utilising argon gas fill

Intensity (Candela): intensity is the amount of light radiated in a given direction, measured as Candela (cd). The higher the Candelas the more intense the light.

kcd: kilo-candelas – see cd above

Kelvin: a measure of colour temperature for lamps.

kWh: kilowatt-hour – the total energy used over a period of time.

L70: operating hours at which light output depreciates to 70% of initial

Lamp: source of artificial optical radiation

LED: light emitting diode

LEDi: integrated LED - LED lamp/module incorporating LED control gear, and any additional elements necessary for stable operation of the light source, designed for direct connection to the supply voltage

LEDni: non-integrated LED lamp or module - needs separate control circuitry or LED control gear to operate”.

LEDsi: semi-integrated LED - an LED lamp/module which carries the control unit of the LED control gear, and is operated by the separated power supply of the control gear

Light output ratio (LOR): the ratio of the total amount of light output of a lamp and luminaire to that of just the bare lamp.

Lumen (lm): unit of luminous flux, used to describe the amount of light produced by a lamp. The higher the lumens, the more visible light emitted by the lamp.

Luminaire: apparatus which distributes, filters or transforms the light transmitted from a light source, including lamp(s), control gear and all components necessary for fixing and protecting the lamps.

Luminance (Candela/m^2): luminance indicates how bright an object will appear and is measured as candela (intensity) per m2. The higher the luminance the brighter the object will appear.

Lux: the international measure of illuminance, or light falling on a surface (lm/m2)

MV: mains voltage (230/240 V)

MWh: mega-watt hour

NCC: national Construction Code (was Building Code of Australia)

Nominal (or rated): the manufacturer’s rated value for a lighting component

PAR: parabolic aluminised reflector (lamp)

PCB: printed circuit board

Rated life: the number of hours after which half the number of lamps in a batch fail under test conditions.

Re-strike: the time taken for a lamp to illuminate after being switched off and then on again.

SSL: solid state (LED) lighting

Start-up: the time taken for a lamp to illuminate after being switched on from cold.

Transformer: magnetic transformer or electronic step-down converter used to reduce voltage for ELV halogen lighting systems.

Universal operating position: refers to a lamp that can be oriented in any way without affecting light quality.

V: Volts

W: Watts