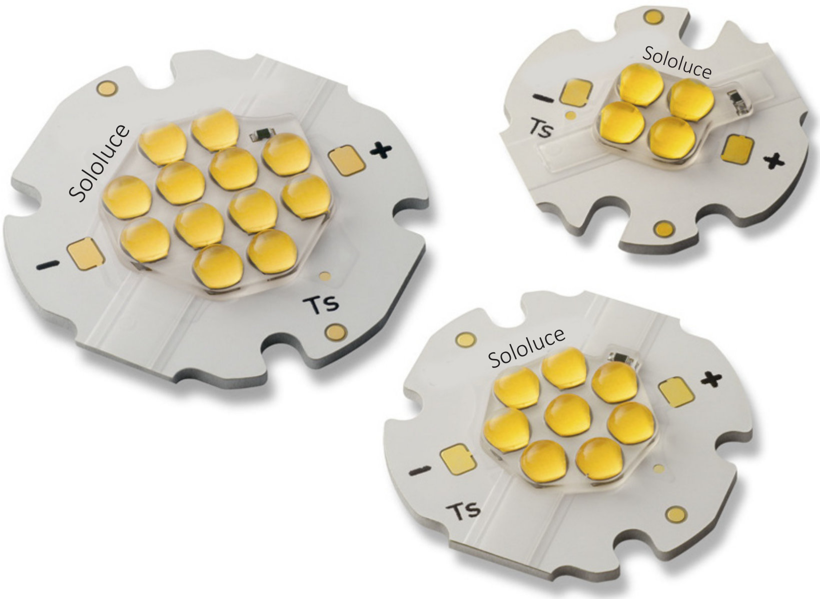
Lighting Talk



LED Lighting Information

Solid-State Lighting Standards

This fact sheet lists the key performance and safety standards applicable to LED-based lighting products.

Product Performance and Measurement Standards

ANSI/NEMA Standards

ANSI/NEMA oversees the creation, promulgation and use of thousands of industry norms and guidelines, including the following key standards of relevance to SSL products.

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C78.377-2008	**Specifications for the Chromaticity of Solid State Lighting Products** • Specifies the recommended chromaticity (color) ranges for white light LEDs with various correlated color temperatures (CCTs).
NEMA SSL-1†	**Power Supply** • Will specify operational characteristics and electrical safety of SSL power supplies and drivers.
C82.77-2002	**Harmonic Emission Limits – Related Power Quality Requirements for Lighting** • Specifies the maximum allowable harmonic emission of SSL power supplies.

IESNA Documents

IESNA is the recognized North American technical authority on illumination.

TM-16-05	**IESNA Technical Memorandum on Light Emitting Diode (LED) Sources and Systems** • This technical memorandum provides a general description of LED devices and systems, and answers common questions about the use of LEDs.
RP-16-05 Addendum a	**Nomenclature and Definitions for Illuminating Engineering** • This document provides industry standard definitions of lighting terms, including all lighting technologies. Addendum a provides definitions of solid state lighting terms.
LM-79-08	**IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products** • Specifies procedures for measuring total luminous flux, electrical power, luminous efficacy, and chromaticity of SSL luminaires and replacement lamp products.
LM-80-08	**IESNA Approved Method for Measuring Lumen Maintenance of LED Light Sources** • Specifies procedures for determining lumen maintenance of LEDs and LED modules (but not luminaires) related to effective useful life of the product.
TM-21†	**Lumen Depreciation Lifetime Estimation Method for LED Light Sources** • Will provide a method for determining an LED luminaire or integral replacement lamp's expected operating life, based on initial performance data collected per IES-LM-80.
LM-XX†	**Method for the Measurements of High-Power LEDs** • Will provide a standardized method for thermal, electrical and photometric measurements of high-power LEDs.

†Currently under development.

NFPA Requirements

70-2005	National Electrical Code • Most SSL products must be installed in accordance with the National Electrical Code.

FCC Requirements

47 CFR Part 15	Radio Frequency Devices • Specifies FCC requirements for maximum allowable unintended radio-frequency emissions from electronic components, including SSL power supplies and electronic drivers.

Color Quality of White LEDs

Color quality has been one of the key challenges facing white light-emitting diodes (LEDs) as a general light source. This fact sheet reviews the basics regarding light and color and summarizes the most important color issues related to white light LEDs, including recent advances.

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit light in a very narrow range of wavelengths in the visible spectrum, resulting in nearly monochromatic light. This is why LEDs are so efficient for colored light applications such as traffic lights and exit signs. However, to be used as a general light source, white light is needed. The potential of LED technology to produce high-quality white light with unprecedented energy efficiency is the impetus for the intense level of research and development currently being supported by the U.S. Department of Energy.

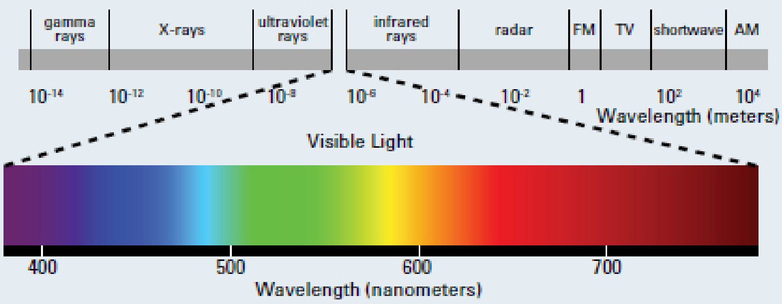
White Light from LEDs

White light can be achieved with LEDs in two main ways: 1) phosphor conversion, in which a blue or near-ultraviolet (UV) chip is coated with phosphor(s) to emit white light; and 2) RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light
.
The phosphor conversion approach is most commonly based on a blue LED. When combined with a yellow phosphor (usually cerium-doped yttrium aluminum garnet or YAG:Ce), the light will appear white to the human eye. Research continues to improve the efficiency and color quality of phosphor conversion.

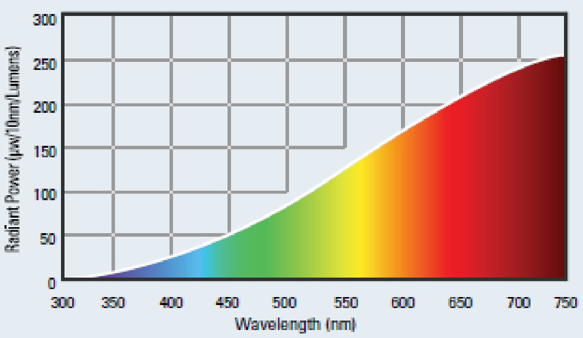
The RGB approach produces white light by mixing the three primary colors - red, green, and blue. The color quality of the resulting light can be enhanced by the addition of amber to "fill in" the yellow region of the spectrum. Status, benefits, and trade-offs of each approach are explored on next page

What is White Light?

We are accustomed to lamps that emit white light. But what does that really mean? What appears to our eyes as "white" is actually a mix of different wavelengths in the visible portion of the electromagnetic spectrum. Electromagnetic radiation in wavelengths from about 380 to 770 nanometers is visible to the human eye.



Incandescent, fluorescent, and high-intensity discharge (HID) lamps radiate across the visible spectrum, but with varying intensity in the different wavelengths. The spectral power distribution (SPD) for a given light source shows the relative radiant power emitted by the light source at each wavelength. Incandescent sources have a continuous SPD, but relative power is low in the blue and green regions. The typically "warm" color appearance of incandescent lamps is due to the relatively high emissions in the orange and red regions of the spectrum.



Example of a Typical Incandescent Spectral Power Distribution

Comparison of White Light LED Technologies

Each approach to producing white light with LEDs (described on previous page) has certain advantages and disadvantages. The key trade-offs are among color quality, light output, luminous efficacy, and cost. The technology is changing rapidly due to intensive private and publicly funded research and development efforts in the U.S., Europe, and Asia. The primary pros and cons of each approach at the current level of technology development are outlined below.

Technology	Advantages	Disadvantages
Phosphor conversion	• Most mature technology • High-volume manufacturing processes • Relatively high luminous flux • Relatively high efficacy • Comparatively lower cost	• High CCT (cool/blue appearance) • Warmer CCT may be less available or more expensive • May have color variability in beam
RBG	• Color flexibility, both in multicolor displays and different shades of white	• Individual colored LEDs respond differently to drive current, operating temperature, dimming, and operating time • Controls needed for color consistency add expense • Often have low CRI score, in spite of good color rendering

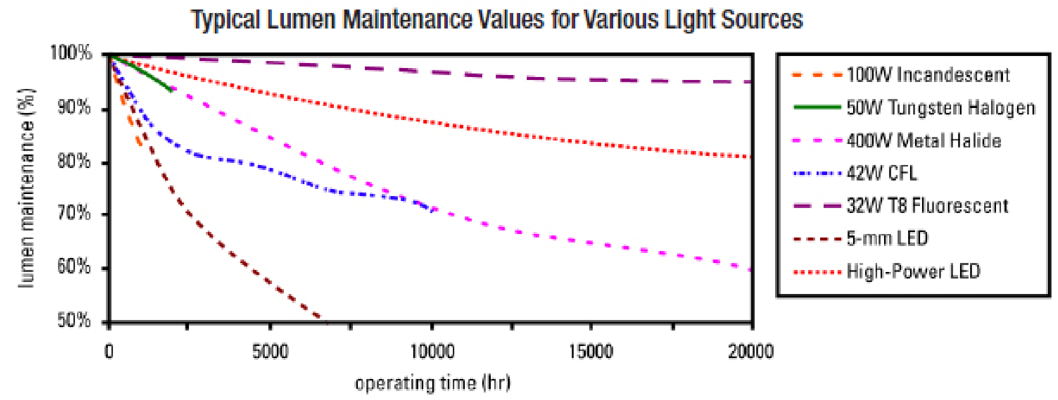
Most currently available white LED products are based on the blue LED + phosphor approach. Phosphor-converted chips are produced in large volumes and in various packages (light engines, arrays, etc.) that are integrated into lighting fixtures. RGB systems are more often custom designed for use in architectural settings.

Lifetime of White LEDs

One of the main "selling points" of LEDs is their potentially very long life. Do they really last 50,000 hours or even 100,000 hours? This fact sheet discusses lumen depreciation, measurement of LED useful life, and the features to look for in evaluating LED products.

Lumen Depreciation

All electric light sources experience a decrease in the amount of light they emit over time, a process known as lumen depreciation. Incandescent filaments evaporate over time and the tungsten particles collect on the bulb wall. This typically results in 10-15% depreciation compared to initial lumen output over the 1,000 hour life of an incandescent lamp.
In fluorescent lamps, photochemical degradation of the phosphor coating and accumulation of light-absorbing deposits cause lumen depreciation. Compact fluorescent lamps (CFLs) generally lose no more than 20% of initial lumens over their 10,000 hour life. High-quality linear fluorescent lamps (T8 and T5) using rare earth phosphors will lose only about 5% of initial lumens at 20,000 hours of operation. The primary cause of LED lumen depreciation is heat generated at the LED junction.



Source: Adapted from Bullough, JD. 2003. *Lighting Answers: LED Lighting Systems*. Troy, NY. National Lighting Product Information Program, Lighting Research Center, Rensselaer Polytechnic Institute.

LEDs do not emit heat as infrared radiation (IR), so the heat must be removed from the device by conduction or convection. Without adequate heat sinking or ventilation, the device temperature will rise, resulting in lower light output. While the effects of short-term exposure to high temperatures can be reversed, continuous high temperature operation will cause permanent reduction in light output. LEDs may continue to operate even after their light output has decreased to very low levels. This becomes an important factor in determining the effective useful life of the LED.

Defining LED Useful Life

To provide an appropriate measure of useful life of an LED, a level of acceptable lumen depreciation must be chosen. At what point is the light level no longer meeting the needs of the application? The answer may differ depending on the application of the product. For a common application such as general lighting in an office environment, research has shown that the majority of occupants in a space will accept light level reductions of up to 30% with little notice, particularly if the reduction is gradual.
Therefore a level of 70% of initial light level could be considered an appropriate threshold of useful life for general lighting. Based on this research, the Alliance for Solid State Illumination Systems and Technologies (ASSIST), a group led by the Lighting Research Center (LRC), recommends defining useful life as the point at which light output has declined to 70% of initial lumens (abbreviated as L_{70}) for general lighting and 50% (L_{50}) for LEDs used for decorative purposes. For some applications, a level higher than 70% may be required.

Terms

Lumen depreciation – the decrease in lumen output that occurs as a lamp is operated.
Rated lamp life – the life value assigned to a particular type lamp. This is commonly a statistically determined estimate of average or median operational life. For certain lamp types other criteria than failure to light can be used; for example, the life can be based on the average time until the lamp type produces a given fraction of initial luminous flux. Life performance curve – a curve that presents the variation of a particular characteristic of a light source (such as luminous flux, intensity, etc.) throughout the life of the source. Also called lumen maintenance curve.

Measuring Light Source Life

The lifetimes of traditional light sources are rated through established test procedures. For example, CFLs are tested according to LM-65, published by the Illuminating Engineering Society of North America (IESNA). A statistically valid sample of lamps is tested at an ambient temperature of 25° Celsius using an operating cycle of 3 hours ON and 20 minutes OFF. The point at which half the lamps in the sample have failed is the rated average life for that lamp. For 10,000 hour lamps, this process takes about 15 months.

Full life testing for LEDs is impractical due to the long expected lifetimes. Switching is not a determining factor in LED life, so there is no need for the on-off cycling used with other light sources. But even with 24/7 operation, testing an LED for 50,000 hours would take 5.7 years. Because the technology continues to develop and evolve so quickly, products would be obsolete by the time they finished life testing.

The IESNA has developed a procedure (IES LM-80) for measurement of lumen maintenance for LED devices (e.g., LED packages, arrays, modules); however, this method does not cover LED luminires or integral replacement lamps. LM-80 also does not provide guidance for estimating or extrapolating lumen maintenance behond the 6,000 hour measurement period prescribed in the test method. To address long-term performance of LED products, the IESNA is currently developing a companion estimation method (IES TM-21) to estimate LED lumen maintenance and service life beyond 6,000 hours. TM-21 will utilize LM-80 data collected at multiple operating temperatures. Because of their potentially long life and impracticality of complete testing, estimates of the life of LEDs will likely be based on the extrapolation of limited test data. It is, therefore, important at this technology's early stage to be conservative in design decisions based on expected useful life.

LED Lifetime Characteristics

How do the lifetime projections for today's white LEDs compare to traditional light sources?

Light Source	Range of Typical Rated Life (hours)* (varies by specific lamp type)	Estimated Useful Life (L_{70})
Incandescent	750-2,000	
Halogen incandescent	3,000-4,000	
Compact fluorescent (CFL)	8,000-10,000	
Metal halide	7,500-20,000	
Linear fluorescent	20,000-30,000	
High-Power White LED		35,000-50,000**

*Source: lamp manufacturer data.

**Depending on drive current, operating temperature, etc. some manufacturers are claiming useful life (L_{70}) values greater than 100,000 hours.

Electrical and thermal design of the LED system or fixture determine how long LEDs will last and how much light they will provide. Driving the LED at higher than rated current will increase relative light output but decrease useful life. Operating the LED at higher than design temperature will also decrease useful life significantly. Most manufacturers of high-power white LEDs estimate a lifetime of around 30,000 hours to the 70% lumen maintenance level, assuming operation at 350 milliamps (mA) constant current and maintaining junction temperature at no higher than 90°C. However, the thermal robustness of LEDs continues to improve, allowing for higher drive currents and higher operating temperatures. For example, manufacturers of high-power white LEDs typically estimate a lifetime of around 50,000 hours to the 70% lumen maintenance level, assuming operation at 700 milliamps (mA) constant current or higher, at maintained junction temperatures above 100°C.

Luminaire Efficacy

The use of light-emitting diodes (LEDs) as a general light source has forced changes in test procedures used to measure lighting performance. This fact sheet describes the concept of luminaire efficacy and the technical reasons for its applicability to LED-based lighting fixtures.

Lighting energy efficiency is a function of both the light source (the light "bulb" or lamp) and the fixture, including necessary controls, power supplies and other electronics, and optical elements. The complete unit is known as a luminaire.

Traditionally, lighting energy efficiency is characterized in terms of lamp ratings and fixture efficiency. The lamp rating indicates how much light (in lumens) the lamp will produce when operated at standard room/ambient temperature (25 degrees C). The luminous efficacy of a light source is typically given as the rated lamp lumens divided by the nominal wattage of the lamp, abbreviated lm/W. The fixture efficiency indicates the proportion of rated lamp lumens actually emitted by the fixture; it is given as a percentage. Fixture efficiency is an appropriate measure for fixtures that have interchangeable lamps for which reliable lamp lumen ratings are available. However, the lamp rating and fixture efficiency measures have limited usefulness for LED lighting at the present time, for two important reasons:

1) There is no industry standard test procedure for rating the performance of LED devices or packages.
2) The luminaire design and the manner in which the LEDs are integrated into the luminaire have a material impact on the performance of the LEDs.

These two issues are discussed in greater detail below. Given these limitations, how can LED luminaires be compared to traditional lighting technologies? As an example, the table below compares two recessed downlight fixtures, one using a 13-watt CFL and the other using an array of LEDs. The table differentiates data related to the light source and data resulting from actual luminaire measurements. Luminaire photometry shows that in this case the LED fixture has input wattage and light output similar to the CFL fixture, and matches the CFL product's luminaire efficacy. This example is based on a currently available, residential-grade, six-inch diameter downlight. LED downlight performance continues to improve rapidly, with some LED retrofit products surpassing CFL downlights in luminaire efficacy.

Example: Comparison of CFL and LED Downlight Luminaires		
Light Source		
Lamp lumen rating	860 lm	
Light source wattage	13 W	*1 W*
LED manufacturer declared "typical luminous flux"		*~100 lm per LED**
Number of lamps/LEDs per fixture	1	12
Luminaire Measurements		
Luminaire lumens	514 lm	589 lm
Measured luminaire wattage	12 W	14 W
Fixture efficiency	60%	
Luminaire efficacy	42 lm/W	42 lm/W

Items in *italics* are not based on industry standard test procedures as published by ANSI/IESNA.
*Depends on specific LED used. Estimate is based on "typical luminous flux" declared by LED manufacturer on the product datasheet, which assumes 25°C LED junction temperature.

No LED rating standard

Traditional light sources (incandescent, fluorescent, and high-intensity discharge) are rated for luminous flux according to established test procedures. In contrast, there is no standard procedure for rating the luminous flux of LEDs. LED light output estimates (as reported on manufacturer datasheets) are typically based on a short (<1 second) pulse of power applied to the LED chip, usually with junction temperature held at 25 degrees C. This is because LED chips must be binned for luminous flux and color during the manufacturing process. To run them any longer without a heat sink would damage them. LED manufacturers usually list "minimum" and "typical" luminous flux on their product datasheets. There is no standardization of the test conditions, or the meaning of "typical." Further, there is no standard test procedure for measuring the luminous flux of LED arrays, such as multiple LEDs mounted on a circuit board.

Impact of luminaire design

For all light sources, there is a difference between rated luminous flux of the lamp and actual performance in a luminaire. However, traditional light sources installed in luminaires operate relatively predictably because the performance of traditional light sources in a wide range of luminaire types, applications, and use conditions is well documented and understood. LED technology is at a far earlier stage of development, so experience and documentation of performance within luminaires is lacking. The efficiency of LEDs is very sensitive to heat and optical design, which increases the relative importance of luminaire design. Ensuring necessary light output and life of LEDs requires careful thermal management, typically requiring the use of the fixture housing as a heat sink or at least as an element in the heat removal design. Luminaires therefore have a fundamental and typically large effect on the luminous flux produced by the LEDs, and on the rate of lumen depreciation over time. LED "drop-in" replacement lamps, such as Edison-based reflector lamps or MR-16 replacements, are in theory designed to provide the necessary heat sinking for the LEDs, but given their installation in fixtures not specifically designed for LEDs, good heat management will be a challenge. In summary, luminous flux—and by extension, luminous efficacy—must be measured at the luminaire level for two primary reasons: 1) no standard procedures are available for rating LED devices on their own, and; 2) the amount of light emitted by a fixture cannot be predicted reliably based on available information about LED devices and fixtures. The lighting industry has adopted luminaire efficacy as the preferred measure of LED performance, as evident in the development of a new test procedure based on this approach

Terms

Photometry – the measurement of quantities associated with light, including luminance, luminous intensity, luminous flux, and illuminance.

Integrating sphere – a device that enables geometrically total luminous flux to be determined by a single measurement. The usual type is the Ulbricht sphere with associated photometric equipment for measuring the indirect illuminance of the inner surface of the sphere.

Goniophotometer – an apparatus for measuring the directional light distribution characteristics of light sources, luminaires, media, and surfaces. Goniophotometry can be used to obtain total luminaire flux (lumens) and efficacy (lumens/watt), but not the color metrics (chromaticity, CCT, and CRI).

Spectroradiometer – an instrument for measuring radiant flux (visible and non-visible) as a function of wavelength. Visible radiation measurements can be converted into luminous intensity (candela) and flux (lumens).

Thermal Management of White LEDs

LEDs won't burn your hand like some light sources, but they do produce heat. In fact, thermal management is arguably the most important aspect of successful LED system design. This fact sheet reviews the role of heat in LED performance and methods for managing it.

All light sources convert electric power into radiant energy and heat in various proportions. Incandescent lamps emit primarily infrared (IR), with a small amount of visible light. Fluorescent and metal halide sources convert a higher proportion of the energy into visible light, but also emit IR, ultraviolet (UV), and heat. LEDs generate little or no IR or UV, but convert only 20%-30% of the power into visible light; the remainder is converted to heat that must be conducted from the LED die to the underlying circuit board and heat sinks, housings, or luminaire frame elements. The table below shows the approximate proportions in which each watt of input power is converted to heat and radiant energy (including visible light) for various white light sources.

Relative Power Conversion for "White" Light Sources

Relative Power Conversion for "White" Light Sources

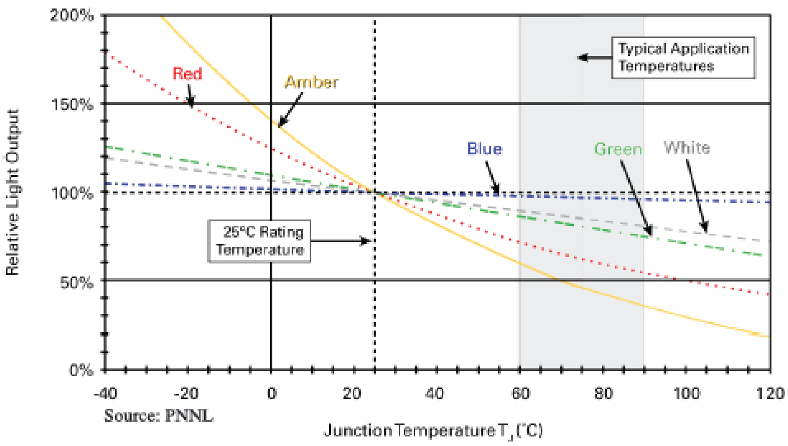
	Incandescent† (60W)	Fluorescent† (Typical linear CW)	Metal Halide‡	LED*
Visible Light	8%	21%	27%	20-30%
IR	73%	37%	17%	~ 0%
UV	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	20-30%
Heat (Conduction + Convection)	19%	42%	37%	70-80%
Total	100%	100%	100%	100%

† IESNA Handbook ‡ OSRAM SYLVANIA

* Varies depending on LED efficacy. This range represents best currently available technology in color termperatures from warm to cool. DOE's SSL Multi-Year Program Plan (Mar 2009) calls for increasing extraction efficiency to more than 50% by 2025.

Why does thermal management matter?

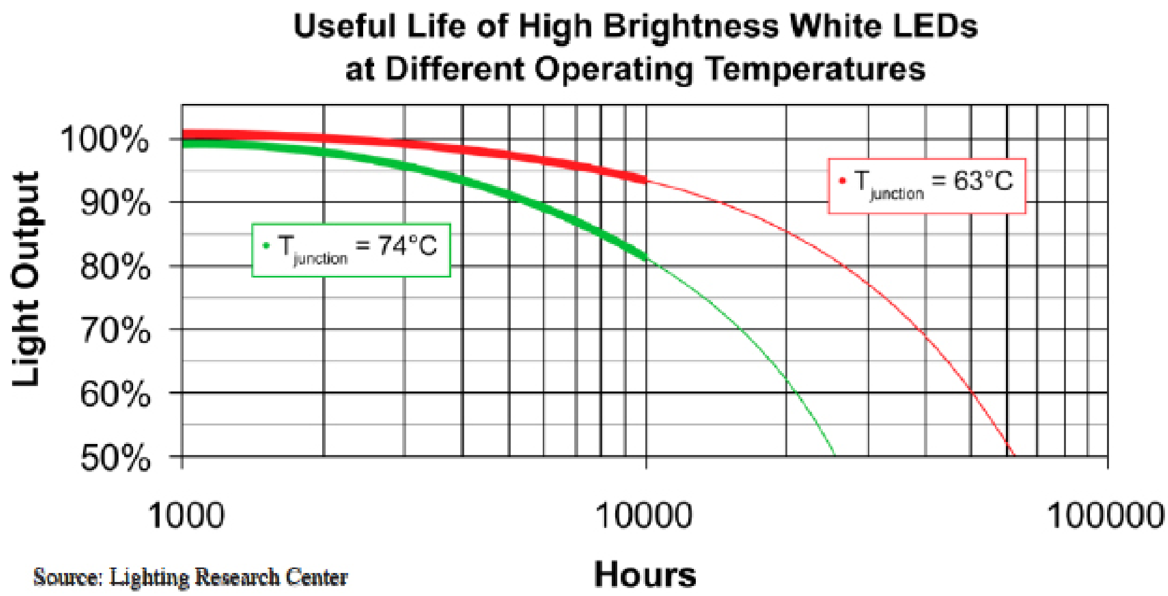
Excess heat directly affects both short-term and long-term LED performance. The short-term (reversible) effects are color shift and reduced light output while the long-term effect is accelerated lumen depreciation and thus shortened useful life.



The light output of different colored LEDs responds differently to temperature changes, with amber and red the most sensitive, and blue the least. (See graph at right.) These unique temperature response rates can result in noticeable color shifts in RGB-based white light systems if operating Tj differs from the design parameters. LED manufacturers test and sort (or "bin") their products for luminous flux and color based on a 25 millisecond power pulse, at a fixed Tj of 25°C (77°F). Under constant current operation at room temperatures and with engineered heat mitigation mechanisms, Tj is typically 60°C or greater. Therefore white LEDs will provide at least 10% less light than the manufacturer's rating, and the reduction in light output for products with inadequate thermal design can be significantly higher.

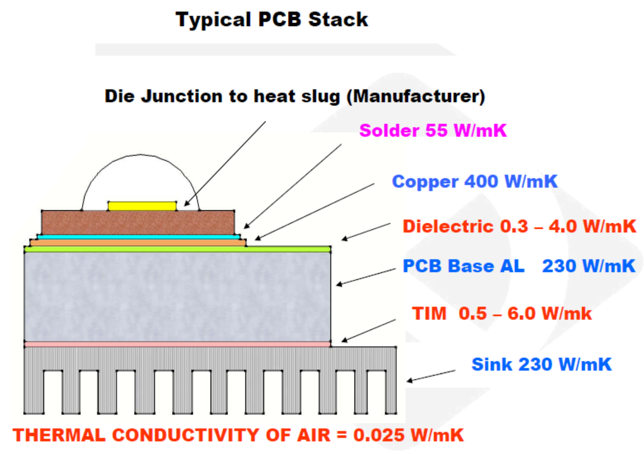
Continuous operation at elevated temperature dramatically accelerates lumen depreciation resulting in shortened useful life. The chart below shows the light output over time (experimental data to 10,000 hours and extrapolation beyond) for two identical LEDs driven at the same current but with an 11°C difference in Tj. Estimated useful life (defined as 70% lumen maintenance) decreased from ~37,000 hours to ~16,000 hours, a 57% reduction, with the 11°C temperature increase.

However, the industry continues to improve the durability of LEDs at higher operating temperatures. For example, manufacturers of high-power white LEDs typically estimate a lifetime of around 50,000 hours to the 70% lumen maintenance level, assuming operation at 700 milliamps (mA) constant current or higher, at maintained junction temperatures above 100°C.



What determines junction temperature?

Three things affect the junction temperature of an LED: drive current, thermal path, and ambient temperature. In general, the higher the drive current, the greater the heat generated at the die. Heat must be moved away from the die in order to maintain expected light output, life, and color. The amount of heat that can be removed depends upon the ambient temperature and the design of the thermal path from the die to the surroundings.



The typical high-flux LED system is comprised of an emitter, metal-core printed circuit board (MCPCB), and some form of external heat sink. The emitter houses the die, optics, encapsulant, and heat sink slug (used to draw heat away from the die) and is soldered to the MCPCB. The MCPCB is a special form of circuit board with a dielectric layer (non-conductor of current) bonded to a metal substrate (usually aluminum). The MCPCB is then mechanically attached to an external heat sink which can be a dedicated device integrated into the design of the luminaire or, in some cases, the chassis of the luminaire itself. The size of the heat sink is dependent upon the amount of heat to be dissipated and the material's thermal properties.

Heat management and an awareness of the operating environment are critical considerations to the design and application of LED luminaires for general illumination. Successful products will use superior heat sink designs to dissipate heat, and minimize Tj. Keeping the Tj as low as possible and within manufacturer specifications is necessary in order to maximize the performance potential of LEDs.

Heat sink design

The applicable heat transport mechanisms are conduction via the heat sink, convection and thermal radiation to the surroundings. The objective of this chapter is not to indicate exactly how to calculate a heat sink, but to give some guidelines on how to improve its performance. Although a heat sink can have many (complex) shapes, the following discussion is based on a disk type of heat sink. The results for square plates, etc., are more or less the same provided the surface areas are equal. The type of material used has a relatively large influence on the final result. For example, a comparison of the thermal conductivity (k) of copper with that of corrosion-resistant steel (below) shows that a substantially smaller heat sink can be made with copper. In practice, the best material for heat sinks is (soft) aluminum.

The thickness (d) of the heat sink disk is also of major importance. Assuming the use of different heat sinks of the same diameter but made from different materials, the same effect in terms of temperature difference will be achieved if the product of thermal conductivity (k) and disk thickness (d) is constant. This means more or less the same result is obtained with a disk of 1 mm copper, 2 mm aluminum, 4 mm brass, 8 mm steel or 26 mm corrosion-resistant steel. Increasing the diameter, and thereby also the surface area, of the heat sink disk also leads to an improvement, but the effect is smaller for larger diameters and depends on the thermal conductivity (k) of the material and the thickness (d).

Thermal radiation can also form a substantial part of the total heat transfer, and is of the same order as for convection. This depends strongly on the emission coefficient (see table) of the surface, which lies between 0 and 1. For example, a polished aluminum surface has a very low emission coefficient, while that of a painted surface is very high.

Thermal conductivity

Material	W/mK
Copper	400
Aluminum	200
Brass	100
Steel	50
Corrosion-resistant steel	15

Emission coefficients

Material	W/mK	Emission coefficient
Aluminium	new/polished	0.04 - 0.06
	oxidized	0.2 - 0.3
	anodized	0.8
Steel	painted	0.8 - 0.95
	new/polished	0.03 - 0.07
	heavily oxidized	0.7 - 0.8

Case temperature and thermal circuit

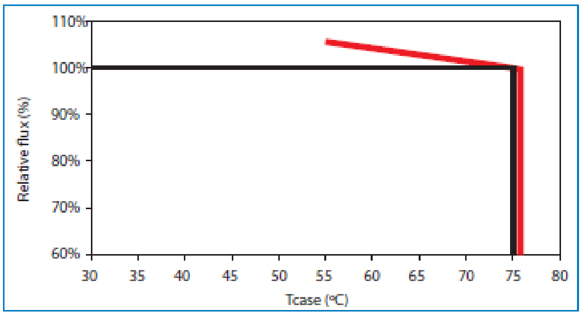
To ensure the performance of the LED Module system, manufacturers define Tc at the back surface of the LED module of say 65º C. At that case temperature the junction temperature of the LEDs is assured and the indicated performances (lifetime, light output, lumen maintenance) can be realized. Above a Tc of 65º C, a thermal circuit will be engaged. This circuit will dim the LED module. The graphs below display the typical case temperature and relative flux as a function of ambient temperature, for a calculated heat sink performance of 1 K/W. The performances of light output, light maintenance and lifetime are related to the Tc value.

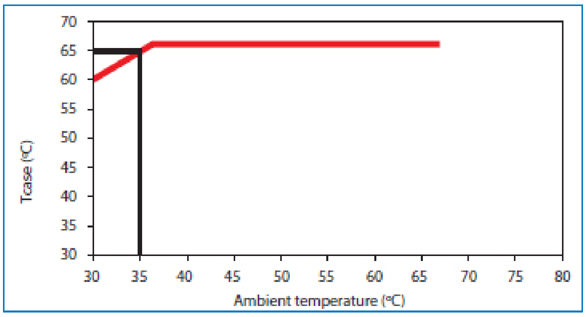
Case temperature and LED module performance

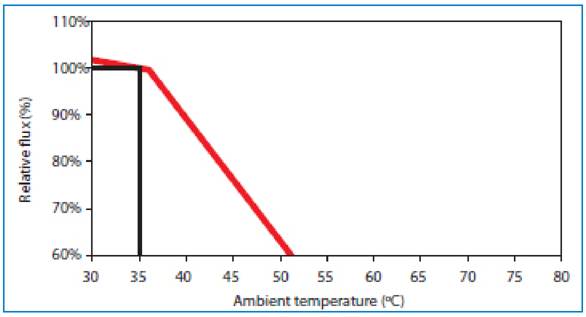
The LED modules which are nominally designed for a case temperature of 65° C/149° F. The flux is then 100%. The graphs below show the relative light output (flux) as a % of the nominal case temperature. As you can see, if the operating condition of the LED module is lower than the Tc point, performance will increase.

Operation in free air

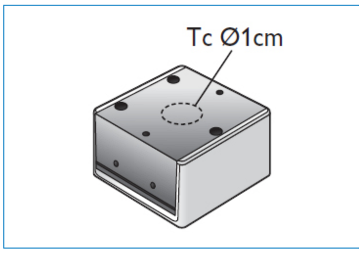
In general LED modules are not designed for operation in free air. Instead LED module has a build-in concept for integration into luminaires.







Size of heat sink



Temperature test point Tc

Figure A

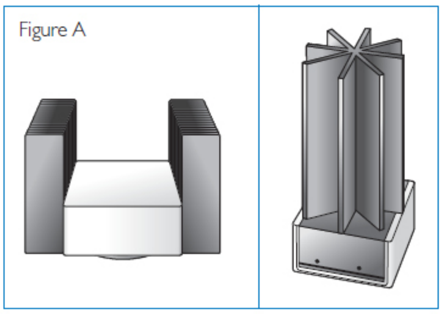
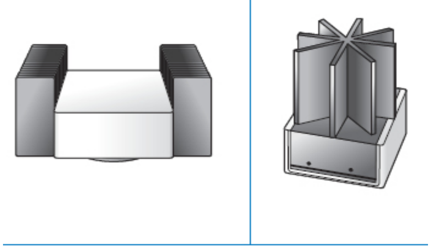


Figure B



Lets consider a LED module that consumes 18 W or 45 W and contain a built-in heat sink. Deducting the driver efficiency and the energy that is effectively giving light leaves a heat dissipation of 15W and 38W, respectively, that needs to be taken away from the module. The sink at the sides and back of the module is the contact area for the external heat sink. The heat sink transports the heat away from the module and is connected to the heat sink, with either the use of the pre-made screw holes or side grooves.
The performance (lifetime and amount of light) of the module depends heavily on the thermal management. Therefore the temperature of the test point (Tc) is important. During the thermal design process, the aim is to keep the Tc temperature below the stated maximum (65° C). Although the LED module will not fail due to a higher temperature, the effect of insufficient cooling will mean that the light output of the LEDs is automatically dimmed , So the better the thermal management (low Tc of the LED module), the better the performance of the luminaire (lifetime and light output). Here is a differentiation opportunity for luminaire manufacturers.

Active and passive cooling

There are two thermal cooling options, passive and active cooling.

Passive cooling systems are made so that hot air moves upwards, and an airflow is created along the surfaces. This is called natural convection.

Active cooling systems have airflow that is forced with a fan or SynJet, which enhances the thermal capacity of the heat sink. As a result, a smaller heat sink can be used and orientation of the heat sink is no issue anymore. Negative aspects of active cooling is the possibility of additional noise caused by a fan, as well as incremental energy consumption. Note that the OEM needs to engineer a cooling solution that matches the entire system’s lifetime and intended application.There are many standard heat sinks available which are relatively cost effective. When comparing active cooling, the form factor of the total system is approximately two times larger.

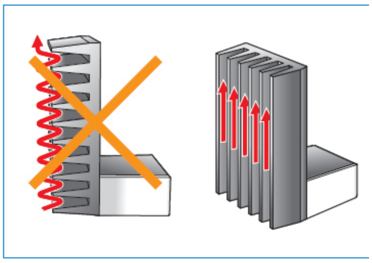
Passive cooling

There are two passive thermal solutions.
As shown on the left sides of Figure A and B, the solution with the heat sinks connected to the sides of the module has the advantage of lower height, but a larger diameter. The disadvantage is an extra thermal resistance path from test point Tc (in the center of the rear surface) to the sides where the heat sinks are connected. As shown on the right sides of Figure A and B, the heat sink is connected to the backside of module. This configuration provides no extra thermal resistance, though to achieve this same cooling capacity, extra height is required.

Air flow

Before starting with any calculation, an important point to consider is the airflow.

In general, hot air is moving upwards with relatively low speed. The form and position of the heat sink is influencing the airlow. In the picture on the left, the the fins are perpendicular to the airflow which reduces the efficiency of the heat sink. This situation should be avoided.



A better way to position the fins is indicated in the picture on the right, where the fins are parallel to the airflow direction. Closing the top of the profile will reduce the effectively of the heat sink as well, and should be avoided during design and installation.

Thermal design

There are two main thermal paths to consider — from the temperature test point to the side surfaces and from the heat sink to the ambient temperature (warming up and dynamic behavior are not discussed here, as a static situation is normally found in lighting applications).

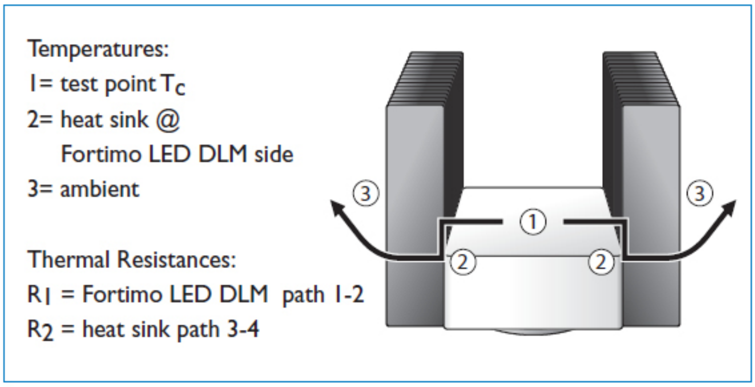
From the temperature test point Tc (point 1) to the side surfaces (point 2)

• This is already measured by manufacturer and is 0.2 K/W. Please note that if you attach the heat sink directly to the back of the module, the 0.2 K/W should be considered.

From the heat sink to ambient (point 3)

The thermal resistance of a heat sink is normally given in a datasheet, but it is based on a few assumptions:

• A certain thermal power has to be applied, as the efficiency of the heat sink is lower at low energy levels
• The temperature of the backside of the heat sink is homogeneous
• An air flow can freely flow over the surfaces



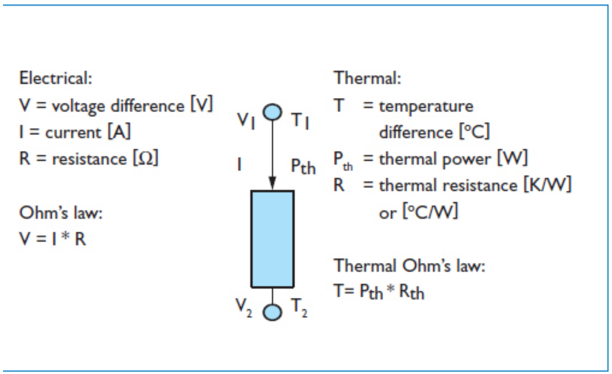
Thermal path basic solutions

Thermal model

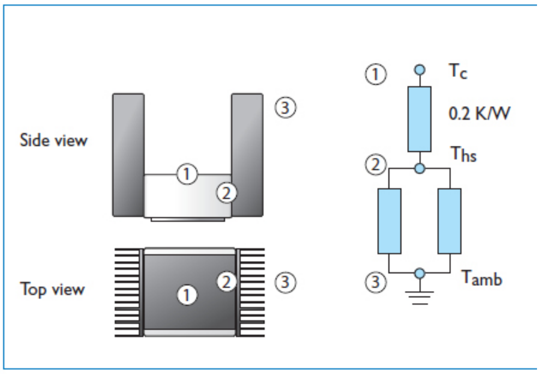
Standard STATIC thermal situations can be modeled with so-called thermal resistances. These resistances behave like electrical resistors. Below the analogy between electrical and thermal resistors is explained. Electrical units are shown on the left, with thermal equivalents shown on the right.

With a known voltage difference at a certain current, it is possible to calculate an electrical resistor with Ohm's law. The same is possible with a thermal resistor. If the temperature difference is known as well as the thermal power, the thermal resistance can be calculated with thermal Ohm's law.

In the figures below you see the two most important thermal resistances.
The following are some notable conditions:
• From test point Tc to side surface of the LED module , where the heat sinks are connected
• From side surface of LED module to ambient. As we have connected two heat sinks, both will have a similar thermal resistance in parallel
• In the specification the maximum Tc is given, in case of a LED module system this is 65° C



Electrical and thermal analogy



Thermal resistance of LED module

Calculating your heat sink

We start with 3 thermal calculation formulas:

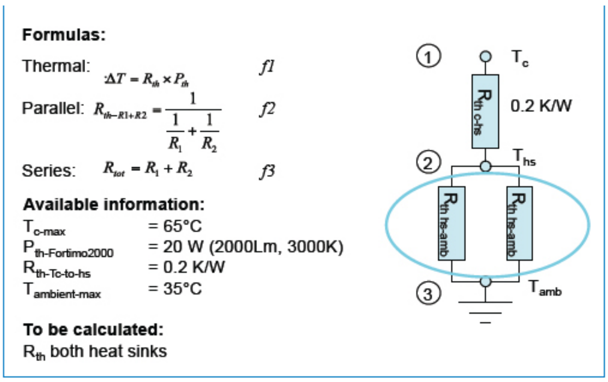
• Formula 1 (f1) is the relation between temperature difference, thermal power and thermal resistance. With this formula, the needed thermal resistance can be calculated when the thermal power and temperature difference are known.
• Formula 2 (f2) shows how to calculate the replacement of two parallel resistors, with one equivalent.
• Formula 3 (f3) shows the replacement equivalent of 2 resistors in series, simply add the values.

Next we gather all available information, as can be found in the datasheet, application details and design choices.
From the datasheet:
Maximum test point temperature: Tc-max = 65° C
Thermal power LED module : Pth = 20 W
Thermal resistance from Tc to side surface: Rth-Tc-to-side-surface = 0.2 K/W
Maximum temperature in application: Tambient-max = 35° C chosen in this case.

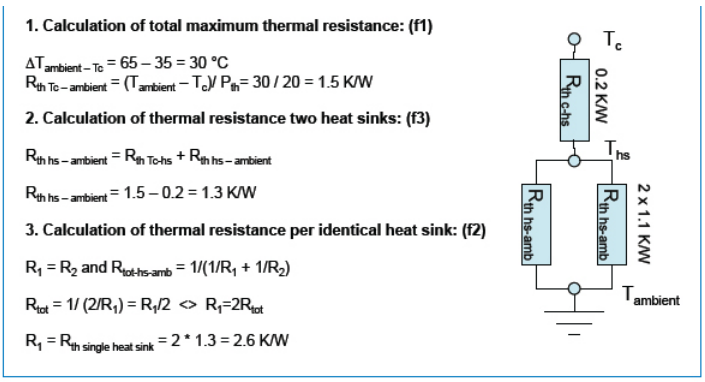
In this case we install the product below ceiling, which is the ambient temperature of the product.

The maximum temperature differs per application and can be lower or higher, than the now chosen 35° C.

Below we calculate the needed thermal resistance of the heat sink, so that in worst case scenarios, the maximum temperature of the test point Tc is below its maximum.

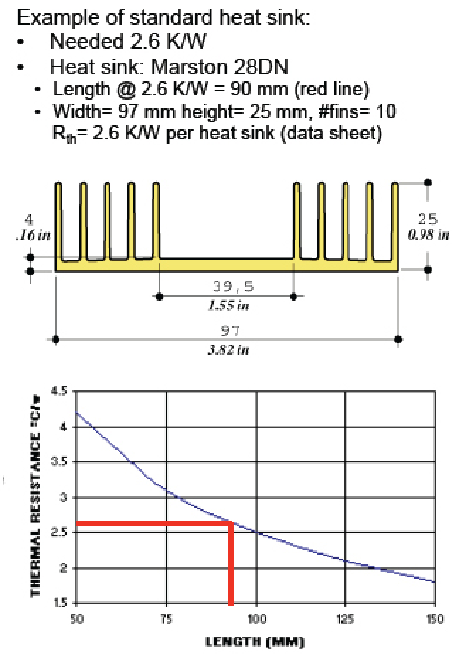


Thermal resistance of heat sink



Thermal resistance of heat sink

Now we know the thermal resistance of the needed heat sink. This heat sink dimension is such that at maximum power and maximum ambient temperature, the temperature of the test point Tc is at or below its maximum of 65° C. This is the worst case scenario, which means that normally the test point temperature Tc is lower. This assures lifetime and light output will be according to specifications.



Thermal resistance of heat sink

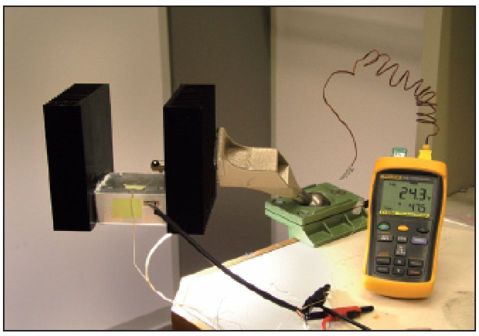
Shape of heat sink

When looking into heat sink suppliers, remember that the shape is determining the thermal resistance of the heat sink. In this case, the length is a design parameter. The graph at left, shows the thermal resistance of the heat sink, with increasing length. With the parameters provided in this example, we need a 2.6 K/W heat sink and the red line indicates that this profile has the stated value with a length of approx. 90 mm.

There are many variations in fin number, length of fins, length of heat sink and so on. With special thermal design software, a tailor-made solution can be found as well.

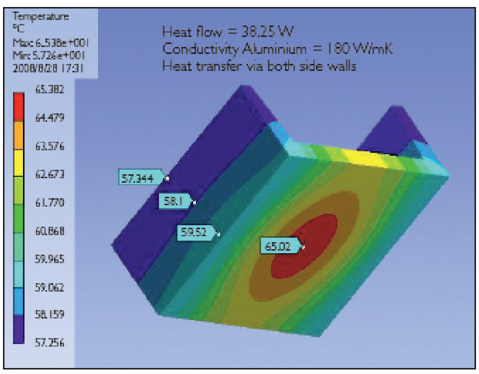
With the use of a standard thermocouple, all important temperatures can be measured and compared to theoretical values.

On the left you see the standard set-up for thermal testing of the LED module system which includes two connected heat sinks and three thermocouples.



Key thermocouple test points are:
• At test point Tc
• At the heat sink interface of the LED module
• At the ambient temperature in situation

With this simple set-up, all important values can be measured and compared to the theoretical values. It's important to assure good thermal contact between LED module and the heat sinks. We recommend using thermal pads or thermal paste. Furthermore, it is very important that there is no moving air in the room. This will influence the measurement heavily.



How to measure Tc

In case you have no direct or easy access to connect a thermo couple to the defined Tc point, we recommend connecting the thermo couple to one of the sides of the LED module .

The heat sink that is integrated in the LED module ensures that temperature difference for Tc point to both sides is minimal. In the visual on the left, you see this difference is approximately 8 degrees with a LED module . If a heat sink is connected to the back of the module, this temperature difference will reduce to 4 degrees.

Understanding Photometric Reports for SSL Products

Given the complex functional relationship between light-emitting diode (LED) light sources and luminaire or replacement lamp components, solid-state lighting (SSL) products do not lend themselves to traditional photometric methods, which were developed separately for lamps and luminaires (i.e., relative photometry). Consequently, the Illuminating Engineering Society of North America (IESNA) developed an SSL product testing method based on absolute photometry, which characterizes a luminaire or replacement lamp as a whole—and acknowledges the unique thermal, optical and electrical properties of these integral products.

The LM-79 Report

IESNA has developed test methods for a broad range of light sources and luminaire types, each providing test protocols specific to the unique attributes of the tested lighting products. For SSL products, LM-79 testing addresses the following key measurements: electrical characteristics, light output, luminous intensity distribution, and color characteristics.
Another important measure of SSL performance, lumen maintenance, is addressed in a separate IESNA test method (IES LM-80-08). LM-79 does not prescribe a specific testing report format or contents, but instead makes the general requirement that the report "··· shall list all significant data for each SSL product tested together with performance data."[1] LM-79 results are critical for evaluating SSL products against application requirements, comparing with other lighting products—and qualifying for the ENERGY STAR® voluntary labeling program.

Electrical Characteristics

LM-79 prescribes the power supply characteristics and electrical instrumentation setup for SSL product testing, and requires that the tested product be operated at its rated voltage (AC or DC). Measurements are typically collected for input voltage (in volts, V), input current (in amperes, A), and input power (in watts, W). These data are used to calculate luminaire efficacy (expressed in lumens per watt, lm/W)—a core indicator of SSL product performance. It is important that separate electrical measurements are taken for each type of photometric test included in the LM-79 report (i.e., integrating sphere and distribution methods discussed below), so that luminaire efficacy is calculated using light output and power measurements from the same test.

Light Output (Luminous Flux)
Essential Data

Zone	Lumens	%FIXT
0-30	702	68.69
0-40	971	95.06
0-60	1021	99.98
0-90	1022	100.00
90-180	0	0.00
0-180	1022	100.00

Figure 1. Detail from Typical Zonal Lumen Summary Table

Total light output (i.e., luminous flux, expressed in lumens, lm) can provide a general indication of how a lighting product stacks up against application needs and/or products it is intended to replace. By extension, luminaire efficacy (lm/W) indicates how efficiently the product generates its light output. Both total light output and luminaire efficacy are major criteria for ENERGY STAR qualification. LM-79 allows two different methods for measuring total luminous flux, one or both of which may be referenced in a test report. The integrating sphere method, as the name suggests, integrates the total light output of a tested source to produce a single measurement. In contrast, the distribution (i.e., goniophotometer) method collects multiple luminous intensity measurements around the source's horizontal and vertical axes, which are converted and summed as total luminous flux. Total light output measurements may be presented as a single value, or as the summed values in zonal lumen summary tables. The sample zonal lumen summary in Figure 1 shows the cumulative lumen totals for different vertical angle "zones," with the 0° – 180° zone (highlighted) representing the total light output (in the case of this recessed downlight, no light is emitted above 90° vertical). If both integrating sphere and goniophotometry have been performed, then two sets of total light output and luminaire efficacy values may be provided—these values may differ by 3% due to typical measurement uncertainties. ENERGY STAR for SSL also establishes zonal lumen requirements for many applications, to help ensure that SSL products perform similarly to the traditional lighting products they replace.

Calculating Luminaire Efficacy

Although input power and light output values may be presented in multiple locations and formats within an LM-79 report, a luminaire efficacy value might not be included in the document. Calculating this value is straightforward, following a few simple steps:

Step #1 Note the tested product's total light output—either a single value from an integrating sphere test, or a summed zonal lumen value from a goniophotometer test. For example, the total lumen output value from the zonal lumen summary table in Figure 1 is **1,022 lm**.

Step #2 Note the measured input power *from the same photometric test as the total light output*. For this example, assume a value of **23.3 W**.

Step #3 Divide the total light output by input power to obtain the tested product's luminaire efficacy. Completing the example:
1,022 lm / 23.3 W = **43.9 lm/W**

Luminous Intensity Distribution

Essential Data

In addition to how much light an SSL product produces, it is important to understand where the product directs its light output. LM-79 reports typically present luminous intensity distribution data in both tabularand polar graph formats. A polar graph allows the reader to quickly assess whether the luminaire or replacement lamp has a "narrow" or "broad" distribution, and gauge its symmetry. For example, Figure 2 illustrates an SSL downlight that produces its highest luminous intensity directly below the fixture (i.e., 0°or nadir), tapering off with essentially no light output above 45° vertical. The solid and dashed lines represent two vertical "slices" made along and across the fixture (i.e., at 0° and 90° horizontal, respectively). The two distributions are nearly identical, suggesting that the light distribution ("beam") is essentially symmetrical about the vertical axis. The polar graphs correspond with tabular intensity data for different vertical and horizontal angles (expressed in candelas, cd), and may be referred to as a "candela distribution" or "candlepower summary." Luminous intensity values are a key component of illuminance calculations, and distribution data can be provided by the testing laboratory in standardized "IES file" electronic format, compatible with lighting calculation and visualization software.

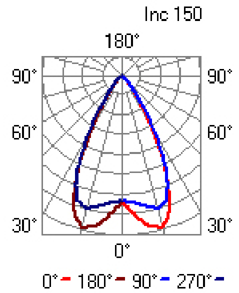


Figure 2. Sample Polar Luminous Intensity Distribution Graph. *Image credit: Luminaire Testing Laboratory, Inc.*

Useful Features

Luminous intensity distribution data inform a range of other lighting metrics used to characterize visual comfort and SSL product performance. Directional lamps, such as halogen MR16 and PAR lamps, are typically characterized by their center beam candlepower (CBCP) and beam angle, and these measures are useful when comparing LED replacement lamps with their traditional counterparts. Although CBCP and beam angle are often not included in LM-79 reports, they can be approximated from tabular intensity data (see "Comparing Directional Lamps").

Comparing Directional Lamps

If not presented in the LM-79 report, CBCP and beam angle for directional LED replacement lamps can be derived from tabular intensity data. Figure 3 presents the candela (intensity) distribution data for an LED PAR38 replacement lamp, and a corresponding polar intensity graph. The important features of the table are the **vertical angles** (left column) and **intensity data** for each vertical angle (right column). Vertical angles describe the location of data points relative to the center beam (or axis) of the lamp, as illustrated in the polar intensity graph. As is common for directional lamps, only one set (plane) of intensity data is provided, and the beam is assumed to be symmetrical around its central axis.

With the lamp pointed downward, a vertical angle of 0° describes the center of a directional lamp's beam, the single point at which the CBCP is determined—in this case, **1855 cd** (yellow highlight). **Beam angle** is defined as **two times the vertical angle** at which the intensity is **50% of the maximum**. In this example, the maximum intensity is the CBCP (1855 cd) and 50% maximum occurs at approximately 15° (green highlight). Because this vertical angle describes only one-half of the beam, the beam angle would be approximately **30°**.

The CBCP and beam angle data should be used to verify the claimed values from the LED replacement lamp's packaging and/or catalog listing. The data can also be compared with that for halogen MR16 lamps to determine if the LED product will provide the "punch" and distribution needed for the lighting application.

DEG	CANDELA
0	1855
5	1742
15	954
25	291
35	68
45	22
55	15
65	10
75	5
85	2
90	1

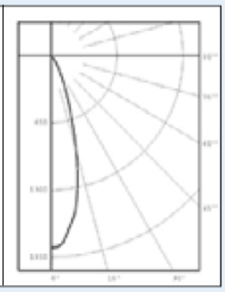


Figure 3. Sample Tabular Intensity Data and Polar Intensity Plot for an LED PAR38 replacement lamp. *Image credit: Independent Testing Laboratories, Inc.*

Luminance summaries (expressed in candelas per square meter, cd/m2) are structured similarly to luminous intensity tables, with data that roughly correlates with perceived "brightness" of a light source from different observer positions. As an example, excessive luminance—particularly at higher vertical angles—could potentially result in visual discomfort from glare. Many test reports also provide an isoilluminance plot, an illustration of a tested product's predicted illuminance pattern and resulting initial light levels (expressed in footcandles, fc). As shown in Figure 4, the diagram (also called an "isofootcandle plot") uses contour lines to delineate the light pattern and horizontal illuminance levels below the tested product, with a conversion chart included for different mounting heights. The scale of the x and y axes is expressed in multiples of the mounting height, so it is important to convert to actual distances and use the same mounting heights when comparing with other products.

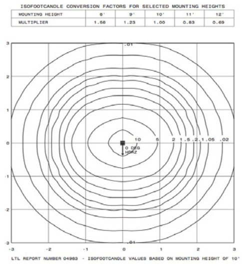


Figure 4. Sample Isoilluminance Plot with Mounting Height Conversion Factors. *Image credit: Luminaire Testing Laboratory, Inc.*

Color Characteristics

Essential Data

SSL luminaires and lamps may be used to replace and/or integrate with other traditional "white light" products. Consequently, it is important to measure and describe SSL color characteristics. LM-79 prescribes methods for measuring the total radiant power (spectral content) of SSL products, from which chromaticity coordinates, correlated color temperature (CCT), and color rendering index (CRI) can be derived. ENERGY STAR for SSL also establishes application-specific limits for these measures. Typically, a product's spectral power distribution (SPD) is presented in a graph format (Figure 5), which allows the reader to evaluate the relative amount of radiant power (expressed in milliwatts per nanometer, mW/nm) across the range of wave- lengths in the visible spectrum (expressed in nanometers, nm), or approximately 380 – 780 nm. Some reports may provide spectral radiant power measurements in tabular format, in 10 nm increments.

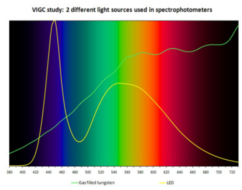


Figure 5. Sample Spectral Power Distribution (SPD) Graph. *Image credit: Lighting Sciences Inc.*

Useful Features

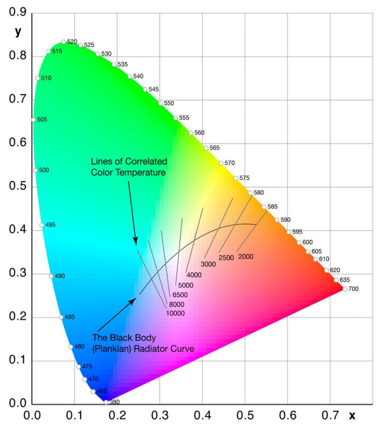


Figure 6. Sample CIE 1931 x, y Chromaticity Diagram, illustrating a tested product's coordinates (indicated by "÷") on the blackbody locus. *Image credit: OnSpeX*

Test reports provide chromaticity coordinates blackbody locus (x, y; u, v; and/or u', v'), and typically plot these values on the corresponding CIE chromaticity diagram (Figure 6), giving a visual indication of where the tested product falls on the "blackbody locus," along which "white light" is defined for lighting products.5 The Duv value, i.e., the plotted distance of chromaticity coordinates from the blackbody locus, describes the relative "whiteness" of light for a given CCT. Productswith excessive Duv values can appear off-white (e.g., pinkish or greenish). Duv can be calculated, or requested if not available on reports

Additional Information

Thermal Measurements

LED performance and service life are closely tied to the LED's operating temperature, which can be extrapolated from readings at a designated temperature measurement point (TMP, also known as a "hot spot") on the SSL luminaire or replacement lamp. LM-79 does not address product operating temperature or its measurement; however, TMP data is required separately under LM-80 for LED lumen maintenance life testing. Having surface temperature measurements also allows the reader to determine if a sample product was operating at similar temperatures in different photometric tests, as different operating temperatures could affect light output and efficacy.

Sample and Testing Description

Test reports should identify the testing laboratory and clearly indicate that LM-79 was used, as well as identify the photometric methods used (integrating sphere and/or goniophotometer) and a listing of the testing equipment used. Some reports may also provide equipment calibration dates and/or descriptions of reference standards and their traceability. Because SSL product performance is closely linked to its components, physical construction and thermal characteristics, it is important that the report explicitly identify the particular version of the product tested. Attention should also be paid to secondary optics and other accessories (e.g., lenses, diffusers, trimrings, etc.) that can affect product performance, and whether these items were in place during testing.

Conclusions

Photometric reports for SSL products under LM-79 present basic measures—electrical, light output and efficacy, light distribution, and color characteristics—that inform a number of other useful report features. For example, luminous intensity distribution data form the basis of polar intensity graphs, fixture luminance tables, and isoilluminance plots. Spectral radiant flux measurements are used to generate SPD graphs and tables, as well as determine chromaticity coordinates, CCT and CRI. Even if not included in a particular lab report, the data and information discussed here is typically collected by and available from the testing laboratory
at their customer's request.

Ambient temperature calculation for LED fixture

LED luminaire with an off-the-shelf heat sink with a thermal resistance of 0.47°C/W. With the heat sink thermal resistance value, the maximum ambient temperature can be calculated with the following formula:

$$T_j = T_a + (R_{th\ b\text{-}a} \times P_{total}) + (R_{th\ j\text{-}sp} \times P_{LED})$$

T_j = LED junction temperature
T_a = Ambient temperature
$R_{th\ b\text{-}a}$ = Heat sink thermal resistance
P_{LED} = Single LED power consumption
= (Operating current) x (Typical Vf @ Operating current)
P_{total} = Total power consumption = (# LEDs) x P_{LED}
$R_{th\ j\text{-}sp}$ = LED package thermal resistance

Example luminaire values:
$T_{j\ MAX}$ = 80°C
$R_{th\ b\text{-}a}$ = 0.47°C/W
P_{LED} = 0.35 A x 3.3 V = 1.155 W
P_{total} = 16 x 1.155 W = 18.48 W
$R_{th\ j\text{-}sp}$ = 8°C/W

$$T_{a\ MAX} = T_{j\ MAX} - (R_{th\ b\text{-}a} \times P_{total}) - (R_{th\ j\text{-}sp} \times P_{LED})$$

$$T_{a\ MAX} = 80°C - (0.47°C/W \times 18.48\ W) - (8°C/W \times 1.155\ W)$$

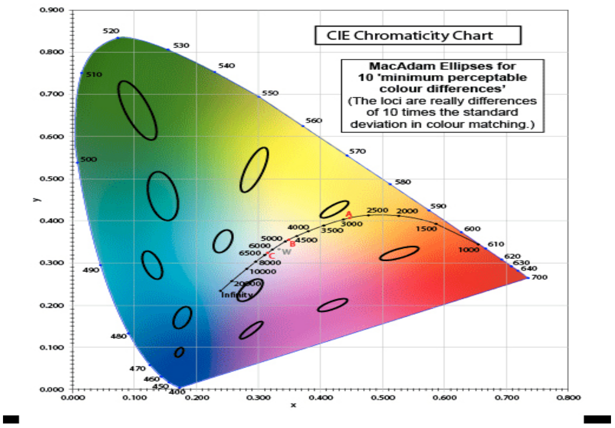
$$T_{a\ MAX} = 80°C - 8.6856°C - 9.24°C$$

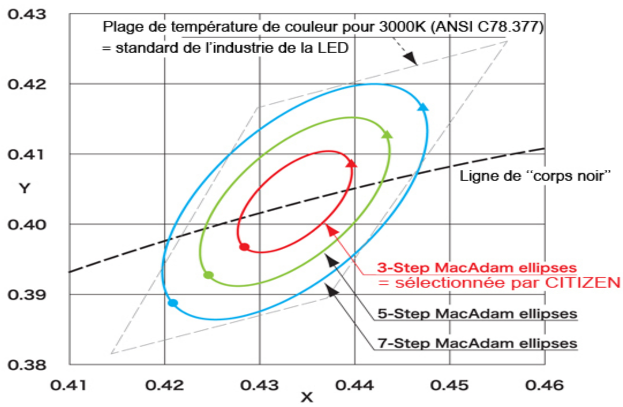
$$T_{a\ MAX} = 62°C$$

A maximum ambient temperature of 62°C for the example luminaire is acceptable for this indoor application. For an operating environment needing higher maximum ambient temperature, either the maximum junction temperature should be raised (which may impact lifetime) or the thermal system ($R_{th\ b\text{-}a}$) improved (e.g., better heat sink).

LED Colour Difference Metrics: SDCM & MacAdam Ellipses

SDCM is an acronym which stands for Standard Deviation Colour Matching. SDCM has the same meaning as a "MacAdam ellipse". A 1-step MacAdam ellipse defines a zone in the CIE 1931 2 deg (xy) colour space within which the human eye cannot discern colour difference. Most LEDs are binned at the 4-7 step level, in other words you certainly can see colour differences





in LEDs that are ostensibly the same colour.

The science behind colour difference specifications was established by Dr David MacAdam in 1942 . MacAdam's experiments relied upon visual observation of the so-called Just Noticeable Colour Difference (JND) between two very similar coloured lights. Just Noticeable Difference is defined as the colour difference where 50% of observers see a difference and 50% of observers do not see a difference. The zones with standard deviations of colour matching (SDCM), were found to be elliptical in the CIE 1931 2 deg observer colour space. The size and orientation of the ellipses varied greatly depending upon the location in the colour space diagram. The zones were observed to be largest in the green and smaller in the red and blue.

Due to the variable nature of the colour produced by white light LEDs, a convenient metric for expressing the extent of the colour difference within a batch (or bin) or LEDs is the number of SDCM (MacAdam) ellipses steps in the CIE colour space that the LEDs fall into. If the chromaticity coordinates of a set of LEDs all fall within 1 SDCM (or a "1-step MacAdam ellipse"), most people would fail to see any difference in colour. If the colour variation is such that the variation in chromaticity extends to a zone that is twice as big (2 SDCM or a 2-step MacAdam ellipse), you will start to see some colour difference. A 2-step MacAdam ellipse is better than a 3-step zone, and so on.

It should be noted that SDCM ellipses are often shown in the CIE colour space diagram at a ten times magnification (see image above) because they would otherwise be too small to be seen clearly when viewed in the complete CIE diagram.
MacAdam's experiments demonstrated that the size of an SDCM ellipse is quite small, which means that the human vision system is very good at discriminating colour differences when viewing two light sources at the same time. If we consider the size of the 1-step SDCM ellipse at an arbitrary 3,000K colour temperature, the CCT range is ±30K, and the corresponding u'v' range (the chromaticity coordinates in the 1976 CIE Uniform Colour Space) is ±0.001. In other words, if we view two LEDs with a CCT difference of more than 60K, the chances are that we will see a colour difference. The table below relates the number of SDCM ellipse steps to the range of CCT and chromaticity coordinates for a 3000K colour temperature light source.

SDCM	CCT @ 3000K	Δ UV
1x	±30K	±0.0007
2x	±60K	±0.0010
4x	±100K	±0.0020
7-8x	±175K	±0.0060

Within the lighting industry, reference is often made to the standard IES LM-79-08 "Approved Method of Electrical & Photometric Measurements of Solid State Lighting Products" published by the Illuminating Engineering Society of North America (IESNA). This in turn references the American standard ANSI C78.377-2008 "Specification for the Chromaticity of Solid State Lighting Products" which places white light LEDs used for illumination into standard colour groups which all have the same "nominal" correlated colour temperatures (CCTs). The size of the ANSI C78.377 nominal CCT quadrangle is a 7-step MacAdam ellipse. A 7 to 8-step SDCM is currently representative of the variation in chromaticity of high brightness white LEDs used for illumination.

Dimming LED Lighting

A luminaire using HB-LEDs is more complex than a typical incandescent or fluorescent fixture, and contains several elements that are specific to the LEDs. Firstly, the LEDs themselves cannot be used directly, but must be mounted onto a circuit board that provides physical support, interconnection and cooling. The complete assembly of LEDs onto the circuit board is commonly referred to as a light engine, which is cooled by a heatsink. Second, the LEDs must be supplied with a DC current that is accurately controlled to provide the required light level without exceeding the LED rating. The current control function is provided by a driver. Finally, in the case of LEDs operating from AC power, there must be a power supply (PSU) that converts the AC into DC for the driver, and provides safety isolation.

Lighting Talk

Fluorescent Lighting Information

SOLOLUCE
ITALY

Main ballast functions

The optimum functioning of fluorescent lamps largely depends on the properties of the control gear used.As with all gas-discharge light sources, fluorescent lamps cannot function properly when they are operated directly from the mains supply voltage. Certain electrical and/or electronic devices have to be built into the lamp circuit, either in the lamp itself or externally in the form of what is called control gear.

The control gear performs a number of functions:

- it limits and stabilises the lamp current, a necessary measure in view of the negative resistance characteristic of gas-discharge lamps (viz. when the lamp current increases, the lamp voltage willdecrease),
- it ensures that the lamp continues to operate despite the fact that twice during each frequency cycle of the mains supply the voltage is zero,
- it provides the ignition voltage (higher than the normal operation voltage) for the initial lamp starting,
- it supplies controlled energy to heat the lamp electrodes during ignition (warm-start ballasts), and in some cases also during normal operation (regulating ballasts).

In addition to these basic functions, the control gear must fulfil a number of other, equally important requirements. It must:

- ensure a sufficiently high power factor,
- limit the harmonic distortion of the mains current,
- if possible, present a high impedance to frequencies used for switching purposes in automatic frequency-regulation circuits (AFRC or Actadis) in outdoor applications,
- offer adequate suppression of any electromagnetic interference (EMI) that might be produced by the lamp/ballast system and that could otherwise interfere with other electronic equipment,
- limit the short-circuit current and/or the current during running-up of the lamp, to protect the lamp electrodes from overloading,
- switch off the lamps when these cannot be ignited normally.This safety requirement is only valid for the HF ballasts,
- keep the lamp voltage, lamp current and lamp power within the specification during mains-voltage variations.

Finally, there is a third group of requirements dictated by the needs of both luminaire manufacturer and user: to have control gear of small dimensions, long life, low losses (also with a view to controlled temperature), and a non-audible noise level.

With the electromagnetic control gear system, various separate components, including ballast, starter, capacitors and filter coils, help fulfil all these requirements together with the lamp.

In the case of the electronic HF ballast, and also in the induction lighting system, all the above-mentioned functions have been integrated into one electronic device, which might be called the ‘black box’.

Luminaire classifications

There are basically three ways of classifying luminaires as far as their design and construction are concerned:

1.According to the sort of protection offered against electric shock, viz. electrical safety.
2.According to the degree of protection provided against the ingress of foreign bodies (e.g. dust and moisture).
3.According to the degree of flammability of the supporting surface for which the luminaire is designed.

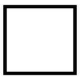
The following are summaries of the classifications detailed in IEC 598 - Part 1.

Electrical safety

(four luminaire classes)
The electrical safety classification drawn up by the IEC embraces four luminaire classes: Class 0, I, II and III.

The official definitions are too long to be reproduced in full here, but can be summarised as follows:

Class 0 - symbol

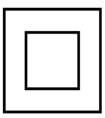


(Note: Applicable to ordinary luminaires only, viz. a luminairewithout special protection against dust or moisture). These are luminaires that are electrically insulated.There is no provision for earthing.The housing may be of an insulating material, which wholly or partly performs the insulating function, or it may be of metal that is insulated from current-carrying parts.Class 0 luminaires may include parts with reinforcedinsulation or double insulation.

Class I - symbol

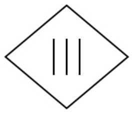
Luminaires in this class, apart from being electrically insulated, are also provided with an earthing point (labelled) connecting all those exposed metal parts that could conceivably become live in the presence of a fault condition. Where the luminaire is provided with a flexible power lead, this must include an earth wire.Where this is not the case, the degree of electrical protection afforded by the luminaire is the same as that afforded by one of Class 0. Where a connection block is employed instead of a power lead, the metal housing must be connected to the earth terminal on the block.The provision made for earthing the luminaire must in all other respects satisfy the requirements laid down for Class I.

Class II - symbol



Class II luminaires are so designed and constructed that exposed metal parts cannot become live.This can be achieved by means of either reinforced or double insulation,there being no provision for protective earthing. In the case of a luminaire provided with an earth contact as an aid to lamp starting, but where this earth is not connected to exposed metal parts, the luminaire is neverthelessregarded as being of Class II. A luminaire having double or reinforced insulation and provided with an earth connection or earth contact must be regarded as a Class I luminaire. However, where the earth wire passes through the luminaire as part of the provisions for through-wiring the installation, and iselectrically insulated from the luminaire using Class II insulation, then the luminaire remains Class II.

Class III - symbol



The luminaires in this class are those in which protection against electric shock relies on supply at Safety Extra-Low Voltage (SELV), and in which voltages higher than those of SELV (50 V AC r.m.s.) are not generated.An AC operating voltage of 42 volt maximum is common. A Class III luminaire should not be provided with a means for protective earthing. The standard ballasts are developed for Class I luminaires. Information for other Classes can be obtained from the local Sololuce Lighting organisation. The earthing of ballasts with metal housing depends on the class and construction of the luminaire. See also IEC 598.

Class 1 luminaire (luminaire has safety earth connection):

1. Metal housing of ballast can be touched during lamp removal. Metal housing must be connected to safety earth (via bottom plate or connector).
2. Metal housing of ballast (incl. ignition aid) cannot be touched during lamp removal.
Only functional earthing is required for proper ignition and EMC

Class 2 luminaire (luminaire has no safety earth connection):

3. Metal housing of ballast (incl. ignition aid) cannot be touched during lamp removal.

Only internal functional connection between ballast and ignition aid is needed for reliable ignition and EMC. Today many luminaires are Class 1 and the metal ballast housing can be touched during lamp removal. All these ballasts must be connected to the safety earth via bottom plate or earth connector if available.

Dust and moisture protection (IP classification)

The IP (International Protection) system drawn up by the IEC classifies luminaires according to the degree of protection afforded against the ingress of foreign bodies, dust and moisture.The term foreign bodies includes such things as tools and fingers coming into contact with live parts.
The designation to indicate the degrees of protectionconsists of the characteristic letters IP followed by two numerals (three numerals in France) indicating conformity with the conditions stated in two tables (here combined into one).The first of these so-called 'characteristic numerals' is an indication of the protection against the ingress of foreign bodies and dust, while the second numeral indicates the degree of sealing against the penetration of water.The third numeral in the French system indicates the degree of impact resistance.

IEC classification according to the degree of dust and moisture protection

Dust protection			**Moisture protection**		
First numeral	**Symbol**	**Degree of protection**	**Second numeral**	**Symbol**	**Degree of protection**
0		Non-protected	0		Non-protected
1		Protected against solid objects greater than 50 mm	1		Protected against dripping water
2		Protected against solid objects greater than 12 mm	2		Protected against dripping water when tilted up to 15°
3		Protected against solid objects greater than 2.5 mm	3		Protected against spraying water
4		Protected against solid objects greater than 1.0 mm	4		Protected against splashing
5		Dust-protected	5		Protected against water jets
6		Dust-tight	6		Protected against heavy seas
			7		Protected against effects of immersion
			8	..m	Protected against submersion

Example: IP 65 indicates a luminaire, that is dust-tight, and waterjet proof.

Degree of flammability of the mounting surface

Luminaires cannot be mounted on just any convenient surface.The flammability of that surface and the temperature of the luminaire mounting plate impose certain restrictions in this respect. Naturally, if the surface is non-combustible, or if a certain distance spacer is employed, there is no problem.
For the purpose of classification, the IEC defines flammable surfaces as being either normally flammable or
readily flammable. Normally flammable refers to those materials having an ignition temperature of at least 200 ºC and that will not deform or weaken at this temperature. Readily flammable are those materials that cannot be classified as either normally flammable or noncombustible. Materials in this category are not suitable as mounting surfaces for luminaires. Suspended mounting is then the only solution. The permitted temperature of that part of the luminaire housing coming into contact with the mounting surface is laid down in the so-called F-requirements. Luminaires that satisfy these requirements may bear the symbol . On the basis of these requirements, the following classification has been drawn up:

IEC luminaire classification according to flammability

Classification	Symbol
Luminaires suitable for direct mounting only on non-combustible surfaces	No symbol, but a warning notice is required
Luminaires without built-in ballasts or transformers suitable for direct mounting on normallyflammable surfaces	No symbol
Luminaires with built-in ballasts or transformers suitable for direct mounting on normally flammable surfaces	F on type plate

Fluorescent Lamps
Range

The low-pressure mercury vapour lamp, or fluorescent lamp, is by far the most widespread of all discharge lamp types. It is employed almost universally: in indoor applications like shops, theatres, etc., in social and civil interiors, but also in street and tunnel lighting. The introduction of the more compact versions has led to its application in homes too. There are many different versions of the fluorescent lamp, including very special lamp types used for reprography, disinfection, sun-tanning, inspection and analysis, various photochemical processes and effect lighting, but they all work on the same principle. It is not the purpose of this Guide to mention all the various types and their sometimes special gear requirements. Technical aspects of the lamps will only be dealt with in,so far as they are directly related to the gear employed. Low-pressure mercury vapour lamps can be divided in,five groups:

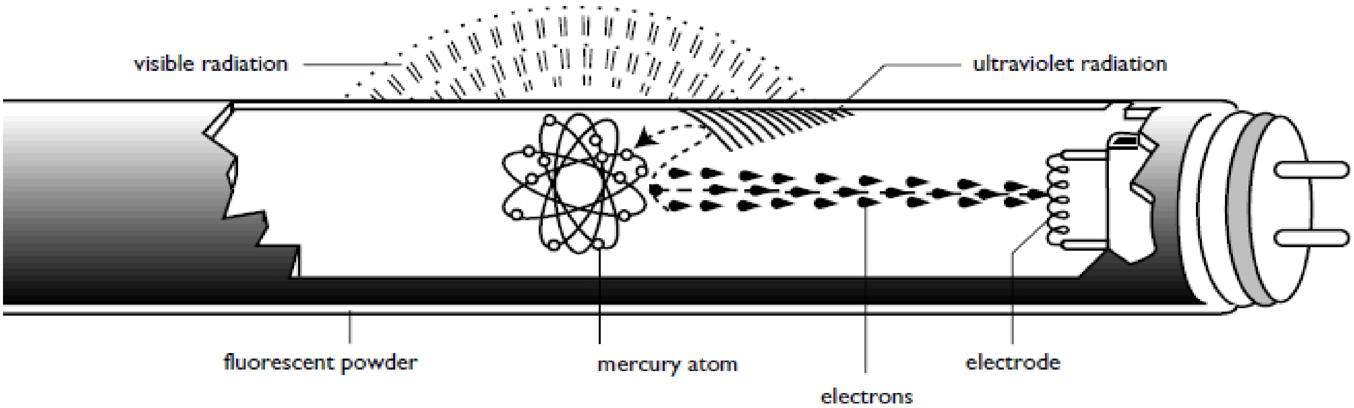


Fig. 17 Working principle of a tubular fluorescent lamp.

1) Tubular fluorescent lamps

The tubular fluorescent lamp works on the low-pressure mercury discharge principle (Fig. 17).
The discharge tube has an electrode sealed into each end and is filled with an inert gas and a small quantity of mercury, the latter being present in both liquid and vapour form.The inside of the tube is coated with a mixture of fluorescent powders.These convert the ultraviolet radiation of the mercury discharge into longer wavelengths within the visible range.A great many different fluorescent powders or 'phosphors' are available for almost any desired colour temperature and colour rendering characteristic. Unlike an incandescent lamp, a fluorescent lamp cannot be connected directly to the mains. Some device to limit the electric current flowing through it must be included in the circuit.This device can be an HF ballast or an electromagnetic ballast with starter.To facilitate starting, the electrodes of most fluorescent lamps are preheated prior to ignition, which is accomplished by means of a preheat current. Starting without preheating of the electrodes is also possible, but at the cost of lamp life, as most lamps are not designed for so-called cold ignition.

The tubular fluorescent lamp group can be further sub-divided as follows (see Fig. 18):

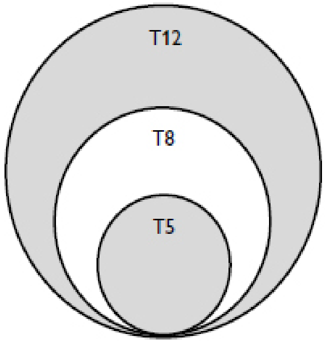


Fig. 18 Comparison of tube diameter of different 'TL' lamps.

a) Straight miniature lamps with G5 lamp cap, with a diameter of 16 mm (code T5, which means that they have a diameter of 5 times 1/8 inch) and with a length dictated by the wattage and by common building modules.This type of lamp can be stabilised with both electromagnetic and electronic gear .
b) Straight 'TL' lamps with a diameter of 38 mm (code T12) and with a length dictated by the wattage and by common building modules.These so-called 'old' or 'thick' 'TL' lamps are stabilised by electromagnetic gear. The normal versions have by now in most cases been replaced by the modern 'lamps, especially in Europe.
c) Straight 'TL'D lamps with G13 lamp cap and 26 mm diameter (code T8), the so-called 'thin' lamps. This most popular krypton-filled type can nowadays be stabilised with both electronic and electromagnetic gear.
d) Straight ‘TL’5 lamps, with higher wattages than the miniature lamps and the benefits of the 'TL'D New Generation lamps.They are 5 cm shorter than the equivalent T8 types and are operated on HF gear.The reason for the reduced length is that optimum compatibility with the most common standard European ceiling systems is obtained that way.

There are two ranges:
'TL'5 HE 14, 21, 28 and 35 W High Efficiency lamps.
'TL'5 HO 24, 39, 49, 54 and 80 W High Output lamps.

2) Bent fluorescent lamps

a) The circular 'TL'E lamp has a special 4-pin lamp cap (G10q) and a diameter of 29 mm (code T9).
They are available in lamp wattages of 22-32-40-60 W and can be stabilised with electronic or electromagnetic ballasts.
b) The U-shaped ‘TL’U has the standard G13 lamp caps and a diameter of 31 mm.Available in lamp wattages 20-40-65 W and are stabilised on electronic or electromagnetic ballasts.
c) The ‘TL’5C (Circular) lamps with lamp cap 2GX13 are in 22 and 40 W with a diameter of 18 mm.They can only be stabilised with HF gear.

3) Non-integrated compact fluorescent lamps

Starting from the straight fluorescent lamp, reduction of the tube length and tube diameter (10 - 16 mm) and combination of two or more such small tubes into one lamp, has led to the PL lamp family with a considerably reduced lamp length. In this way a wide lumen package in small dimensions is obtained.This offers considerable energy savings when used as a replacement for incandescent lamps.

In the case of non-integrated lamps, the lamp and ballastare separated.

In principle they can be sub-divided as follows:

- the PL-S and PL-L /DULUX-L XT with 2 parallel tubes
- the PL-C /DULUX T/E with 4 tubes in square formation
- the PL-T with 6 tubes.

The parallel tubes are connected by bends or bridges, so electrically they are one tube.
Apart from this, various colours are available, and most types are available in two versions:

- 2-pin version, with the starter incorporated in the lamp cap, stabilised with electromagnetic gear, and
- 4-pin version, stabilised with electromagnetic or electronic gear.

Due to the different wattages and versions available, there is a wide variation in lamp caps, information on which can be found in the lamp documentation. Lamp and gear are separated, giving more freedom to the luminaire designer and an increased lifetime of the lighting system, since the lamps can be replaced.

4) Integrated compact fluorescent lamps

The arc tubes and the electronic gear are integrated to form one complete lamp with a standard lamp cap: E14, E27 or B22 for the mains voltage range 230-240 V/50-60 Hz.

Stabilisation

As described earlier , the main ballast function is to stabilise the lamp current, as a fluorescent lamp cannot function properly when it is operated directly on the mains voltage.The first and foremost function of a ballast is to limit the electric current passing through the lamp to a value prescribed for that particular lamp rating. All discharge lamps need such a current-limiting device because they have a negative voltage-current characteristic (see Fig. 19).

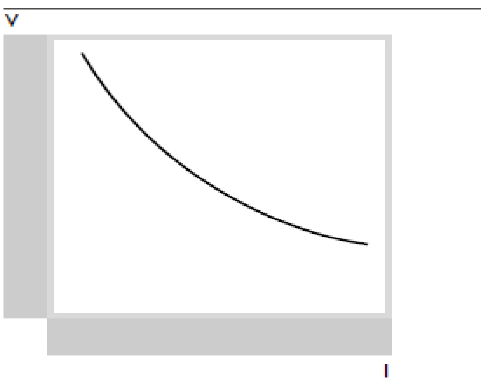


Fig. 19 Current/voltage characteristic of a gas discharge (simplified).The voltage required decreases as the current increases.The characteristic is negative, meaning that the current will without limit if no measures are taken.

Without a current-limiting device in the circuit (lamp voltage = mains voltage), the slightest increase of the lamp current would cause a drop in lamp voltage. But as the mains voltage is still applied to the lamp, the lamp voltage cannot decrease, so the current will now increase even further.This process of steeply rising current will soon cause the lamp to fail or the fuse to blow. On the other hand, at a slight decrease of the lamp current the lamp voltage has to increase.As the mains voltage is still applied, it will become too low for stable operation and the lamp will extinguish.
The presence of a ballast between the lamp and the mains-voltage connection (Fig. 20) limits the current flowing through the lamp.The lamp current – being equal to the ballast current supplied to the lamp – is now fixed by the quotient of the ballast voltage and the ballast impedance.

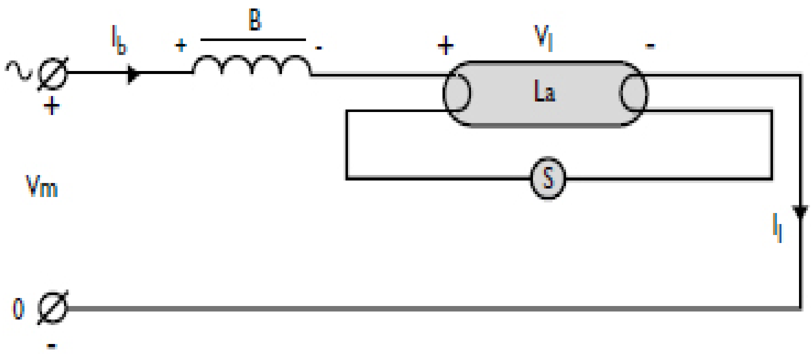


Fig. 20 Current limitation by means of a ballast in a simple discharge circuit.

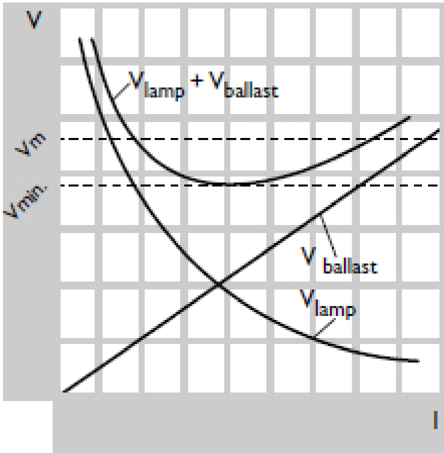


Fig. 21 Current/voltage characteristic of a circuit with a ballast in series with the lamp.Thanks to the ballast, the required lamp voltage increases with increasing lamp current, leading to a stable situation.

As the ballast voltage is the difference between the mains voltage and the lamp voltage, the maximum lamp current is limited by the mains voltage. In this way a stable operating point is obtained for all mains voltages higher than the minimum voltage Vmin (see Fig. 21).

$$I_{lamp} = I_{ballast}$$

$$I_{ballast} = V_{ballast} / Z_{ballast}$$

$$\vec{V}_{ballast} = \vec{V}_{mains} - \vec{V}_{lamp}$$

$$I_{lamp} = (\vec{V}_{mains} - \vec{V}_{lamp}) / Z_{ballast}$$

Another very important function of the ballast is to keep the power consumption of the lamp within certainmargins so as to prevent too high a temperature in the cathodes, which would result in a diminished lamp life.The power of the lamp is equal to the lamp voltage V_{la} times the lamp current Ila times a constant, which is called the lamp factor (α_{la}):

$$P_{la} = V_{la} \cdot I_{la} \cdot \alpha_{la}$$

The lamp factor α la depends on the shape of the lamp voltage and the lamp current, and is therefore also called the 'shape factor'.The value depends on the method of stabilisation and is approx. 0.8 for electromagnetically stabilised lamps and 0.99 for HF stabilised lamps In stable operation the voltage across the lamp is rather constant under all circumstances.Therefore the lamp power (and so the light output) is depends mainly on the lamp current.

The level of the mains voltage is important, as well as the impedance of the ballast.The influence of the frequency of the mains voltage is a hidden factor: this variable influences the impedance of the choke ballast, as $Z = \omega L$ with $\omega = 2\pi f$ (f = frequency).The inductance L is depends on the number of copper windings and the dimensions and material of the core of the ballast. From this it follows that the higher the frequency, the smaller the ballast can be.With the electromagnetic ballast for 50 or 60 cycles we need a 'big' copper/iron ballast, while in the HF ballasts with much higher operating frequencies a small ballast with ferromagnetic material can be employed.

Ignition and run-up

In most cases a cold tubular fluorescent lamp will not start when the mains voltage is applied.This is because the ignition voltage is usually higher than the mains voltage. Some sort of starting aid is therefore needed to ignite the lamp. In practice, this involves one or more of the following solutions:

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

The voltage level at which a fluorescent lamp will ignite is called its ignition voltage. In most lamp types special measures have been taken in the construction of the lamp to keep this ignition voltage as low as possible: the use of a starting gas as a Penning mixture (see Fig. 22) and the application of a starting aid to trigger the initial ionisation of the gas ('TL'M) are examples of this.

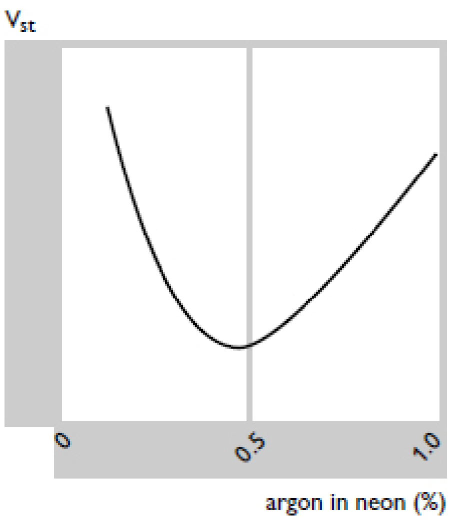


Fig. 22 Starting voltage (Vst) as a function of percentage (%) of argon to neon (Penning effect).

There are three principal ways of igniting the lamp:

1. **The cold start:** ignition is obtained by applying a high initial voltage to the lamp electrodes. Immediate ignition is obtained without any preheating. This method of ignition needs rigid/robust lamp electrodes , a rather high ignition voltage (> 800 V r.m.s.) and enough energy to pass from the initial ignition to the stable burning situation.This procedure is used in the HF-Basic ballasts and is the reason that the switching lifetime of the lamps is less than in the next two systems.

2. **The warm start:** by preheating the lamp electrodes and – once they are at emission temperature –applying a peak voltage just high enough to initiate thedis-charge.The electrodes can be thinner and the applied starting voltage lower (see Fig. 23). The preheat time must be long enough. For the warm-start with an HF ballast a preheat time of approx. 1 second is needed with the correct current, whilst the open-circuit voltage of the lamps is low enough to prevent ignition at this stage.At the end of this time a higher open-circuit voltage will ignite the lamp reliably. Thanks to this procedure, the switching lifetime of the lamps is nearly independent of the switching cycle .

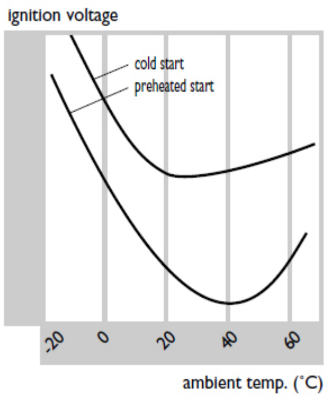


Fig. 23 Influence of ambient temperature on the required ignition voltage, both with cold and with prehea-ted (warm) start.

3**. The rapid start:** here a certain ignition voltage and preheat current are supplied simultaneously to the lamp.As long as the cathodes are not hot enough, the lamp will not ignite.When, after a certain time, the cathodes are hot enough, the lamp will ignite at the applied ignition voltage (see Fig. 24 point P of the socalled Z-curve).

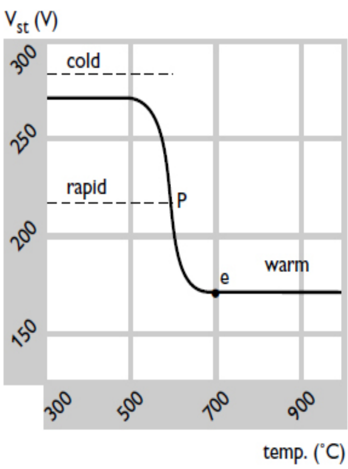


Fig. 24 Starting voltage (Vst) as a function of electrode temperature. Point e represents the emission temperature, viz. the point at which the electrode emits sufficient electrons

Glow-switch starters do function in combination with these ignition systems: as the closing time of the bimetallic contact is not well defined , it is not certain that the lamp electrodes are at emission temperature when the glow-switch starter opens.Also, the height of the ignition peak can vary rather a lot.This can be noticed in practice when the glow-switch starter works several times before the lamp ignites.This flickering gets worse at low ambient temperatures, at low mains voltages, or with aged lamps. The starting of amalgam lamps, requires a higher ignition voltage than that of the standard fluorescent lamps, especially below 10 °C.

The initial ignition (first break-down) results in a low electric current between the two main electrodes. The excitation potential and ionisation potential are very close together, and consequently after a short time many free electrons are present in the discharge, resulting more or less in the nominal lamp current.

After ignition, the lamp will heat up and the temperature of the coldest spot will rise, causing a rise in the mercury vapour pressure, which determines the arc voltage of a given lamp. In what time thermal equilibrium is reached depends on the lamp type and its surroundings (ambient temperature, open/closed luminaire). Normal 'TL' lamps in normal applications have a run-up time of 2-3 minutes to reach stable lamp voltage and a level of 90 per cent of the maximum light output.

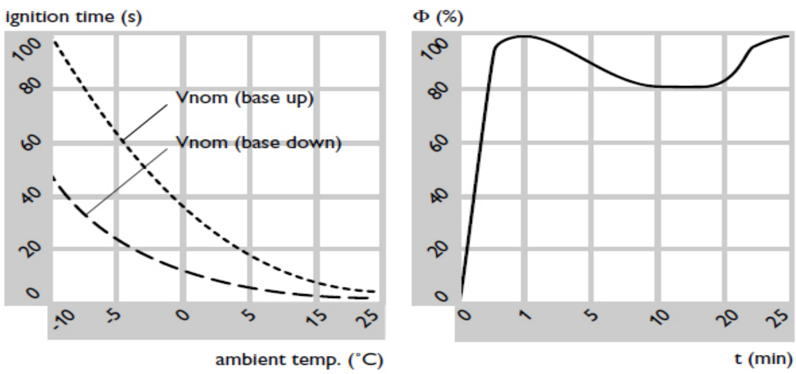


Fig. 25 Typical ignition time and run-up behaviour of an amalgam lamp operated on an electromagnetic ballast

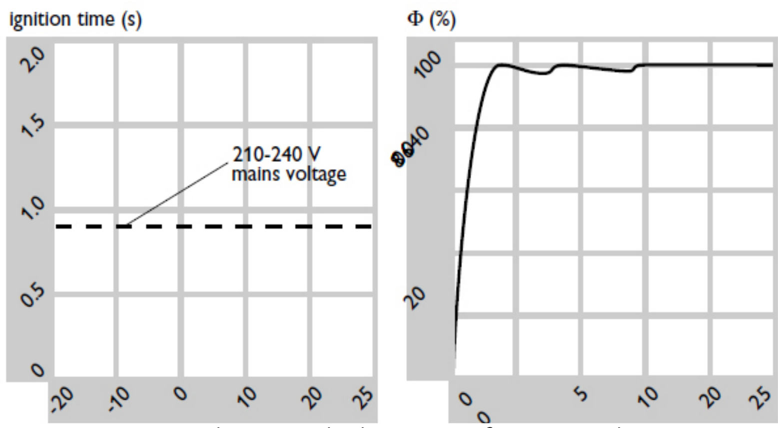


Fig. 26 Typical ignition time and run-up behaviour of a PL*E/C lamp.

The run-up phase for amalgam /induction lamps is longer, due to the amalgam filling. It takes more time for the mercury to evaporate from the amalgam, so it takes longer to reach the stable lamp voltage. But a lighting level of 80 per cent is attained within one minute also with these lamps (see Figs 25 and 26).

Lamp behaviour as a function of the frequency

Supplied by a mains voltage of 230 V/ 50 Hz and stabilised with an electromagnetic ballast, the lamp voltage and lamp current of a fluorescent lamp are not pure sine waves (see Fig. 27).

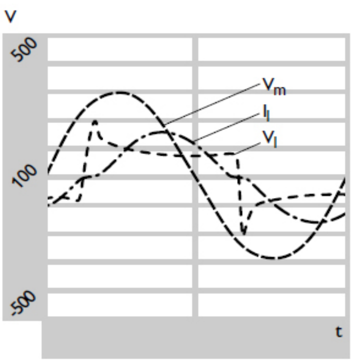


Fig. 27 Waveform of mains voltage (Vm), lamp voltage (Vl) and lamp current (Il).

Every time the current passes through zero, the lamp is'out' and needs a certain re-ignition voltage peak to reignite. The electrical energy supplied to the lamp in the form of Vla and Ila is transformed into the lamp power Wla with a certain lamp factor, called α_{la}, according to
the equation:

$$W_{la} = \alpha_{la} \cdot V_{la} \cdot I_{la}$$

Typical values for an electromagnetically stabilised 50 Hz 'T8-36W lamp are:

V_{la} = 103 volt
I_{la} = 0.44 ampere
W_{la} = 36 watt
so α_{la} = 0.79

The period of time that a lamp is 'out' will decrease by raising the frequency of the lamp current, resulting in a lower re-ignition peak.At increasing frequency both lamp current and lamp voltage will become more sinusoidal, resulting in a higher lamp factor α la (see Fig. 28).
Typical values for a 36 W 'T8 lamp stabilised by HF gear are:

V_{la} = 103 volt
I_{la} = 0.32 ampere
W_{la} = 32 watt
so α_{la} = 0.99

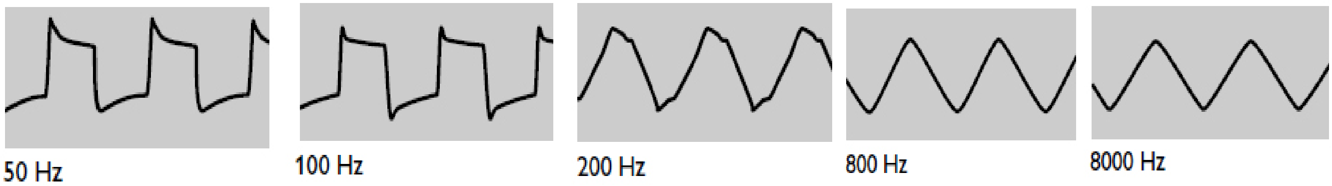


Fig. 28 Lamp voltage as a function of frequency for a'T8- 36 W lamp.

As a result of the improved lamp factor, the lamp current can be lower for a given wattage in the discharge. This reduces the losses in the electrodes even further, giving an extra improvement in lamp efficacy (see Fig. 29).

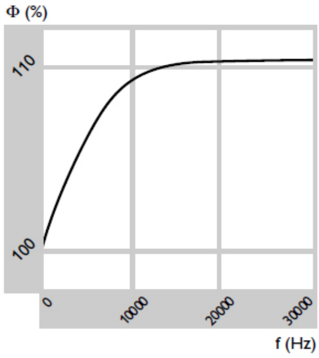


Fig. 29 Luminous flux (Φ) of a fluorescent lamp as a function of supply frequency (f) at constant lamp factor.

For low-pressure mercury vapour lamps at a fixed lamp power, a 10 per cent higher efficiency can be achieved at frequencies of more than 10 kHz.To avoid audible disturbance, the working frequency must be more than 20 kHz. But while much higher frequencies will result in a smaller stabilisation coil, they will also result in higher losses in the electronic switching devices and more radiointerference problems. Different operating frequencies are therefore used, mainly depending on lamp type.The practical working frequency is between 24 kHz and 31 kHz for most HF ballasts .

Lamp and system efficiency

The lamp efficiency is expressed in a figure called the luminous efficacy. It indicates the efficiency of the lamp in transforming electrical energy into light and is expressed in lumen per watt (lm/W).The light or radiated power is 'weighed' according to the eye-sensitivity curve for visible light. The amount of light generated by a lamp is called the luminous flux or lumen output. It is a variable figure, depending on many factors including the phosphors employed (colour), lamp tube dimensions, gas mixture and pressure, and so forth (see Fig. 30 and Table).

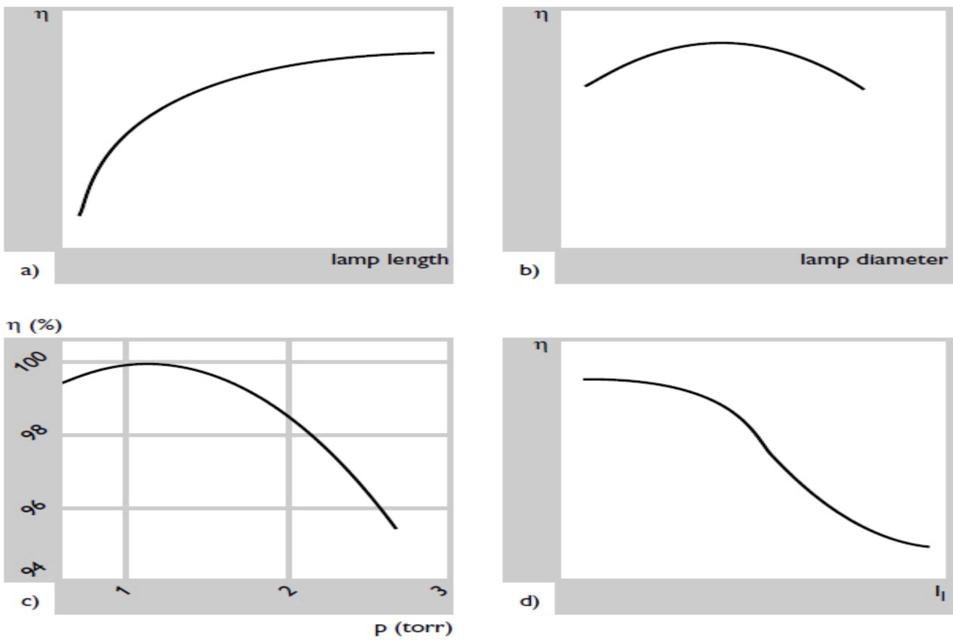


Fig. 30 Lamp efficiency as a function of lamp length (a), lamp diameter (b), argon pressure (c) and current (d).

Indicative comparison of 'TL' lamp generations					
'TL' types from 1945 (4 foot)	Diameter mm	Power W	Luminous flux at 100 hrs lm	Luminous efficacy at 100 hrs lm/W	Luminous flux at 10 000 hrs %
T12Standard	38	40	2850	72	73
T8 Standard	26	36	2850	79	73
T8 Better	26	36	3350	93	85
'T8 with HF ballast	26	32	3200	100	85
T8 with HF better version	26	32	3200	100	92
T5 with HF ballast	16	28	2900	104	92

Note 1: Luminous flux and efficacy are only applicable for colours /827, /830, /835 and /840.

With regard to the gear employed, the working frequency and the lamp current are important.A higher lamp current results in a lower efficiency for certain lamp wattage.The luminous efficacy of all fluorescent lamps increases with the lamp wattage. This is due to the fact that the power needed to keep the lamp electrodes at optimum temperature is relatively lower for higher lamp wattages (longer lamps) than for lower wattages (shorter lamps). All manufacturers publish the Nominal Luminous Flux in their documentation, which is the lamp luminous flux under the following conditions:

- the lamp has burned for 100 hours prior to the readings being taken (burning-in period),
- the lamp is burning in draught free air at a defined ambient temperature (usually 25 °C) and in a specified burning position,
- after switching on, the lamp has had sufficient time to heat up and stabilise for thermal equilibrium,
- the lamp is running at its nominal voltage, nominal current and stabilised nominal mains voltage,
- batches of lamps are read for the average value.

When one of these conditions changes, the nominal flux changes with it. For the total system efficiency, the losses in the gear are important. Since HF ballasts normally have lower losses than the electromagnetic ballasts, the total system efficiency is higher with HF gear than with electromagnetic gear.

Effects of temperature

For every fluorescent lamp there is an optimum for the efficiency related to the pressure of the mercury in the gas-discharge tube.The mercury gas pressure is directly related to the coldest spot of the discharge tube, the socalled 'cold spot'.With straight T8 lamps this cold spot will normally be in the middle of the lamp on the underside. For T5 lamps the coldest spot is at the marking side where the coldest spot is created by a greater distance from the electrode to the lamp end. With PL lamps the cold spot is situated at the lamp ends near the bridge between the separate tubes, see Fig. 31

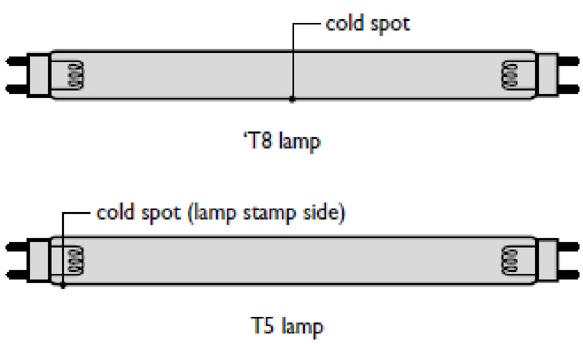


Fig. 31 Cold spots of T8and T5 lamps

Depending on the burning position of the lamp, the temperature of the cold spot can vary and with it also the light output and efficiency (see Fig. 32).The same lamp mounted in a closed luminaire will reach a higher temperature than in an open luminaire, so the lumen output will differ. Graphs are available for all lamps, showing the relative light output of the bare lamp as a function of the ambient temperature. The influence of the luminaire must be found separately by measurement (see Figs 33)
In principle, the gear employed has no influence on the temperature of the cold spot and consequently on the light output.

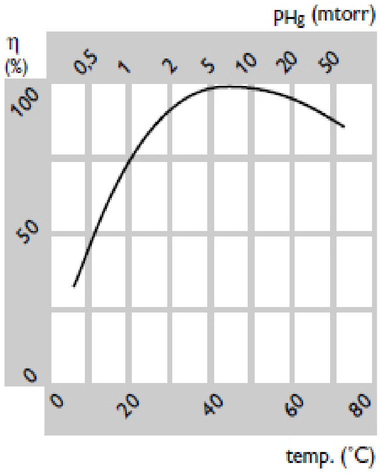


Fig. 32 Lamp efficiency as a function of mercury pressure and ambient temperature.

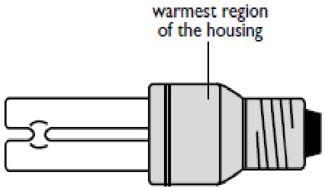


Fig. 33a Warmest region on the housing of a PL lamp.

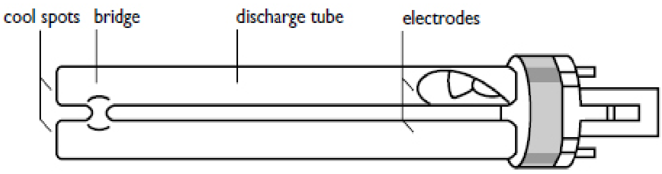


Fig. 33b Cold spot at the tube ends near the bridge of a PL lamp.

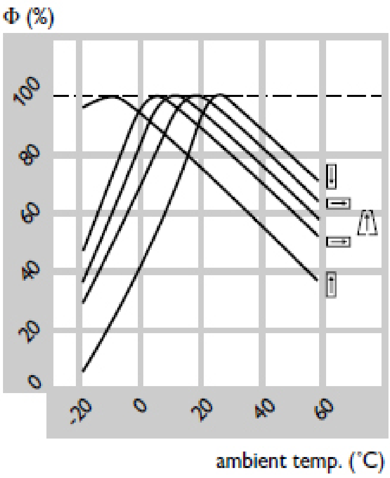


Fig. 33c Relative luminous flux of PL lamps as a function of the ambient temperature and burning position.

Only in closed luminaires will the inside temperature be influenced by the watt losses of the gear. So HF ballasts will have less influence than electromagnetic gear, due to their lower losses.
The optimum mercury vapour pressure for tube diameters of 26 and 38 mm is about 0.8 Pa, and this is reached at a tube wall temperature of about 40 °C. This is not much higher than the usual ambient temperature of 20 to 25 °C, and the heat generated by the discharge is sufficient to reach the required operating temperature of 40 °C without special measures.

If the temperature is low (for example, outdoor lighting in winter), it is desirable to operate the fluorescent lamp in a well-closed luminaire.The new 'T5 lamp is optimised for an ambient temperature of 35 °C. For the luminous flux as a function of the ambient temperature, see Fig. 36 a/b. If the wall temperature is above the ideal operating temperature, artificial cooling of the lamps might be useful, but this requires extra facilities.

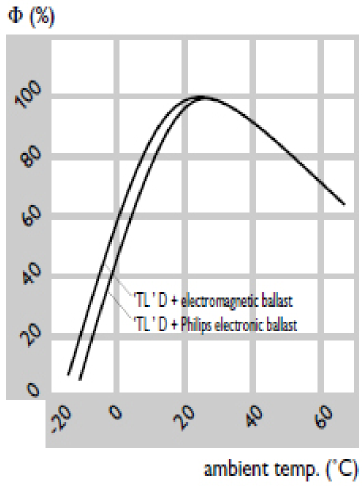


Fig. 36a Luminous flux as a function of ambient temperature for 'TL'D lamps operated on different control gear.

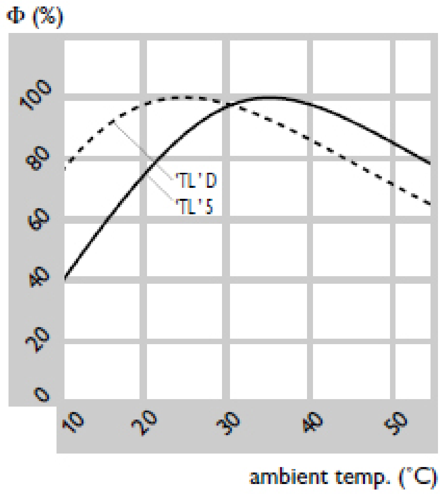


Fig. 36b Comparison of luminous flux as a function of ambient temperature between 'TL'D and TL5 HE lamps.

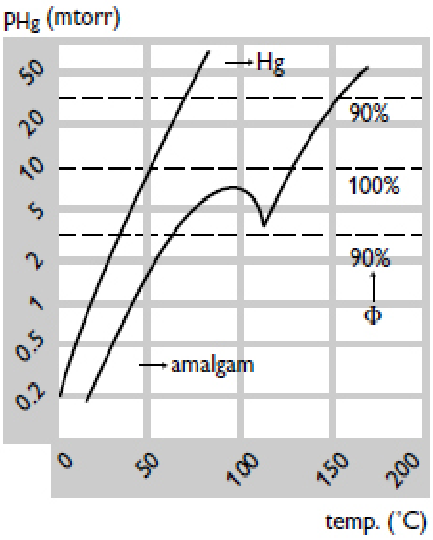


Fig. 37 The influence of amalgam on the mercury pressure and on the luminous output of an amalgam lamp.

By adding amalgam to the mercury gas filling it is possible to guarantee a light output of more than 90 per cent of the maximum in the amalgam temperature region between 550 and 120 °C (see Fig. 37). This measure is taken in induction lamps, where the minimum temperature inside the glass tube is about 90 °C.

Optimum operation

As has been said there are many different types of fluorescent lamps, each in different lamp wattages, lamp voltages and lamp currents.Although the differences in behaviour are not so wide as with high-intensity gas-discharge lamps (SON-SOX-HPL-HPI-MHD), each type has its own pros and cons.
What they have in common though, is that they need the correct ballast and ignition system for optimum performance. In fact, each type needs its own specific gear. For this reason one should take care to use the recommended gear in combination with the chosen lamp. Especially when using electromagnetic ballasts, the combination must be correct for the available mains voltage (220, 230 or 240 V / 50 or 60 Hz). HF ballasts cover a wider mains-voltage range, which can be found in the product data sheets.

When the wrong components are chosen, one can expect problems: for example, with:
- lifetime of lamps and gear
- temperatures
- starting/run-up
- stable burning
- radio interference
- light output

Lamp life and depreciation

The data published by lamp manufacturers for life expectancy and lumen depreciation are obtained from large representative groups of lamps in laboratory tests under controlled conditions (see for example Figs. 38 and 39).These include, amongst others:

- nominal supply voltage and appropriate circuitry
- specified burning position
- specified switching cycle
- free-burning, mounted on test racks (not in a luminaire)
- no vibrations or shocks
- specified ambient temperature, mostly 25 °C.

Any change in these circumstances will affect a lamp's lifetime.

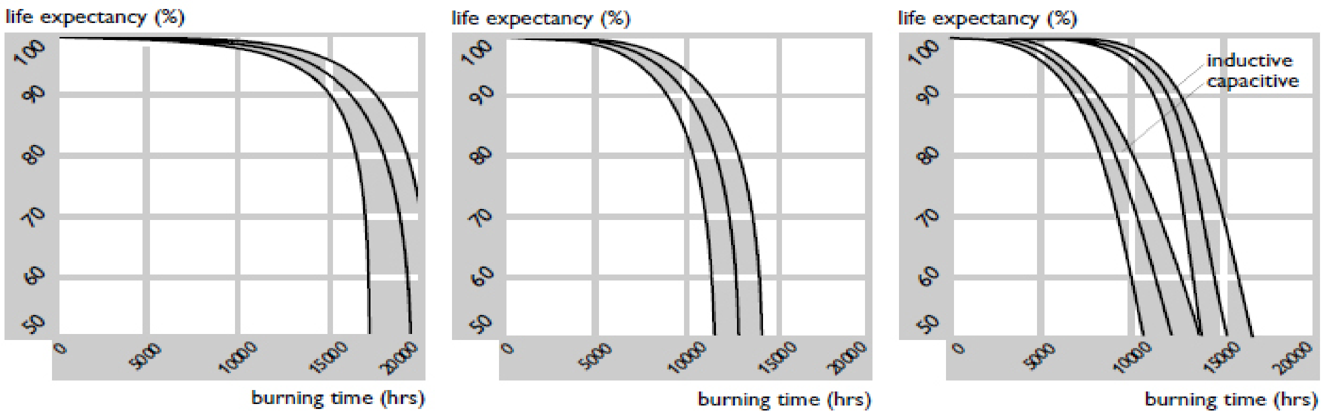


Fig. 38a Life expectancy curve forT8 super/80 New Generation on HF gear; warm start.
Fig. 38b Life expectancy curve forT8 Super/80 New Generation on HF gear; cold start.
Fig. 38c Life expectancy curve forT8Super/80 New Generation on conventional gear.

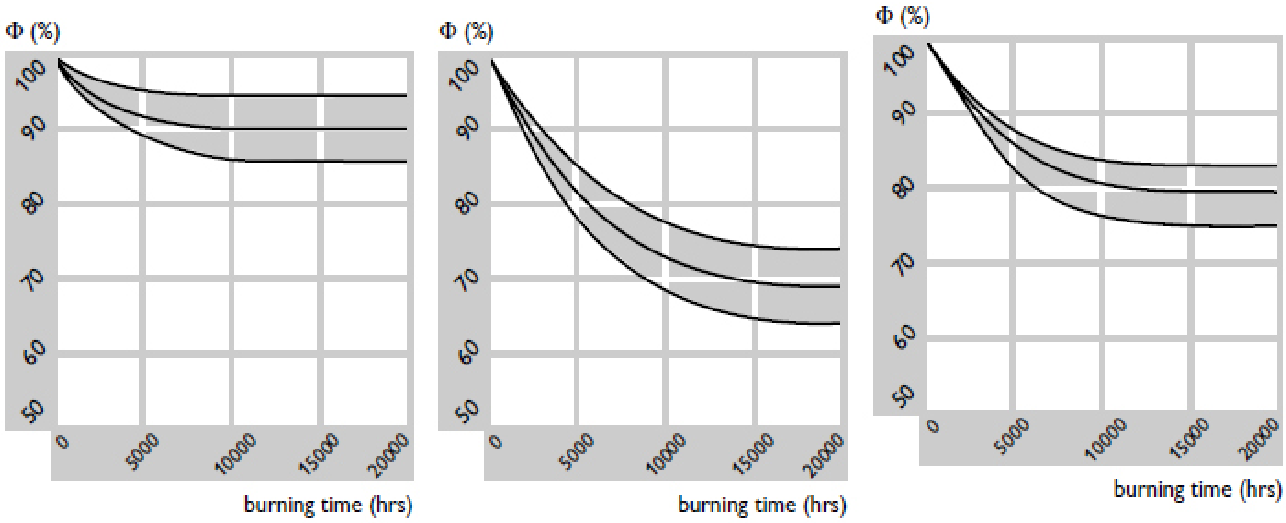


Fig. 39a Lumen maintenance in % for T8 Super /80 New Generation and TL5.
Fig. 39b Lumen maintenance in % for T8 standard colours on conventional gear.
Fig. 39c Lumen maintenance in % for T8 /90 de Luxe colours.

The type of circuitry can also influence lamp life or lumen maintenance. For example, due to the controlled starting process the life expectancy of fluorescent lamps operated on a warm-start HF ballast is higher than on electromagnetic gear.

Lamp life on electromagnetic L and LC circuits

For conventional, electromagnetic operation, the electrodes are preheated when the switch starter is closed.At the moment the switch starter opens, the lamp may or may not ignite.Whether or not the lamp will ignite depends on the 'produced' ignition voltage. This again depends on the mains voltage at the moment the switch starter opens. If the lamp does not ignite, more attempts will follow until the lamp does ignite. Lamp life is also influenced by the type of starter used. For conventional operation, important differences exist between L (inductive) and LC (with series capacitor) operation. For LC operation the preheat current through the electrodes is much lower than with L operation, which results in a lower electrode temperature at ignition. After the lamp is ignited, the lamp current is higher than with L operation.As a consequence the electrode temperature is then relatively high. Because of these differences it is not possible to have the optimum switching behaviour for both L and LC operation.A compromise has to be chosen.The situation is further complicated by the rather strong influence of two different operation conditions:
a) Preheat current and lamp current increase with the mains voltage. In general, lamp life will decrease with increasing mains voltage.
b) The necessary ignition voltage is temperature dependent.This means that results of switching tests will be different for different ambient temperatures.

Lamp life on warm-ignition ballast

With 'warm-ignition' HF ballasts, the electrode is preheated in a well-defined way. After the preheat time, the lamp is ignited with a sufficiently high voltage. Due to the preheated ignition, the performance on faster switching cycles is very good. Lamp life is also improved for slow switching cycles.This is caused by the optimum relation between lamp current and electrode heating current.The presented lamp life values are the average figures over the lamp and ballast range. In comparison with conventional operation:
- performance on fast switching cycles is improved,
- lamp life will not depend on mains voltage (mains independence!),
- lamp life will not depend on ambient temperature

Lamp life on cold-ignition ballast

When 'TL' lamps are operated without the appropriate electrode preheat current, lamp life will be reduced with more frequent lamp ignition. In the past, guidelines have been developed to design the cold ignition in such a waythat the 'ignition damage' is limited. After lamp ignition,the 'glow-to-arc transition' has to take place within 100 ms.This is reached when the ballast delivers the appropriate amount of power during the glow phase (defined by IEC).When this is the case, lamp life will be comparable to operation on a conventional L circuit for switching cycles greater than 5 hours. Also important for lamp life is the electrode temperature during operation. For electronic operation, the heat balance of the electrode differs significantly from that with conventional operation.Without extra electrode heating, a certain minimum lamp current has to be maintained to obtain the appropriate lamp life. For this reason the so-called α -control has been developed: the electrode current is maintained at the optimum value during both the ignition phase and the normal running, and at all dimming levels and temperatures for all IECcompliant lamp types. Another factor influencing the life of fluorescent lamps is the type of phosphors used: the modern lamps with /80 and /90 colours have a con-siderably lower light depreciation during their burning life than do the lamps with other fluorescent materials, say, colour /33 or /25 (see Fig. 39).Specific information on lamp life and light depreciation is in most cases available from the local Lamp organisation.

Influence of switching cycle

Fluorescent lamps may be required to be switched on and off more than only a few times per 24 hours, especially when they are used in combination with controls such as movement detectors or light cells. The influence of the switching cycle on the lifetime of the different types of fluorescent lamps is different in different lamp circuits. The 'average' lamp-life data presented are typical values.They are the average of different tests. Batch deviations occur due to deviations in the materials used and in lamp processing, and to different types and batches of gear. Differences in 'application parameters', such as mains voltage, ambient temperature and starter, can also have a negative influence on lamp life, especially for conventionaloperation.These effects are almost absent for HF operation.The standard deviation of the 'typical' lamp life values is 10 to 20 per cent.

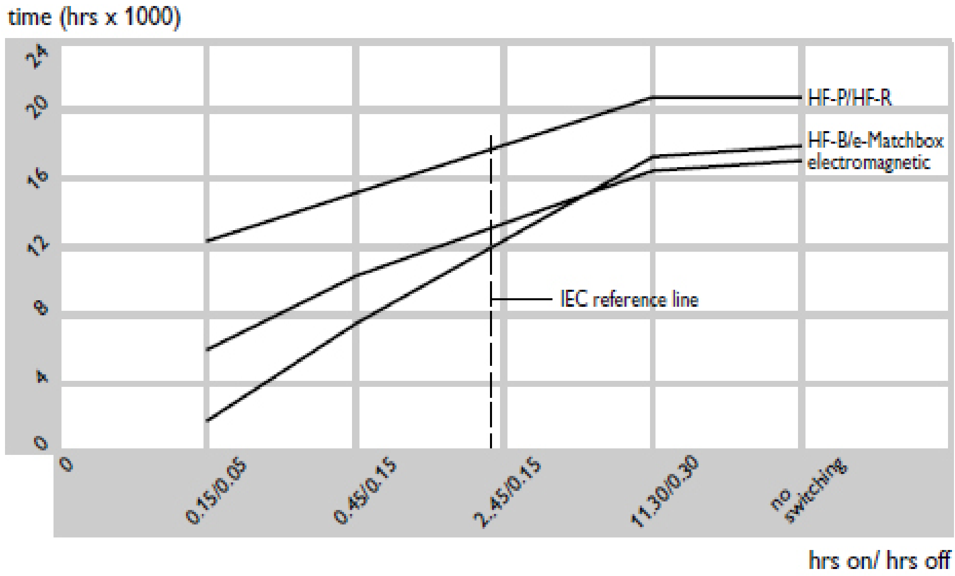


Fig. 40 Influence of switching cycle (in hours per start) on lamp life for 'TL'D.

Stroboscopic effect and striations

The stroboscopic effect is the apparent change of motion of an object when illuminated by periodically varying light of the appropriate frequency. Flicker is the fluctuation of the lamp's light output on account of movement of the discharge arc on the electrodes. Striations are noticeable as a pattern of more or less bright regions in the long discharge tube.This pattern can move through the discharge tube. It can appear when the lamp is cold or when the lamp is dimmed down to too low a level. One or more of these three phenomena may appear, especially in combination with conventional gear In the case of HF ballasts, the first two effects are not notice-able, thanks to the inertia of the fluorescent material, which cannot follow the high operating frequency and also because the ballast limits the light modulation in the 50 Hz mains to a large extent . However, at low ambient temperatures and/or at low dimming levels striations can also occur with HF ballasts.

Electronic lamp control gear
Electronic high-frequency system

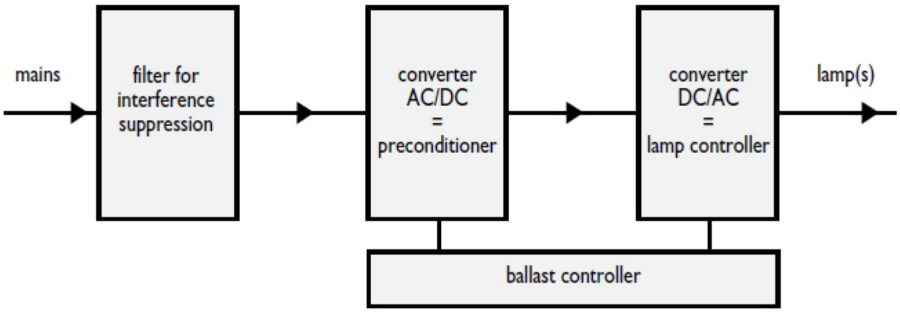


Fig. 43 Block diagram indicating the main functions of an electronic HF ballast system.

Block diagram (see Fig. 43)
Although the electronic HF ballast system is integrated into one single 'black box', its different functions can be divided into a number of individual blocks. In broad outline: after passing a low-pass (RFI) filter, the mains voltage is rectified in an AC/DC converter.This converter also contains the buffer capacitor, which is charged with current via this DC voltage. In the DC/AC converter the DC voltage is transformed into an HF voltage, which provides the power for the lamp controller.The ballast controller controls all these functions

Circuit diagram (see Fig. 44)

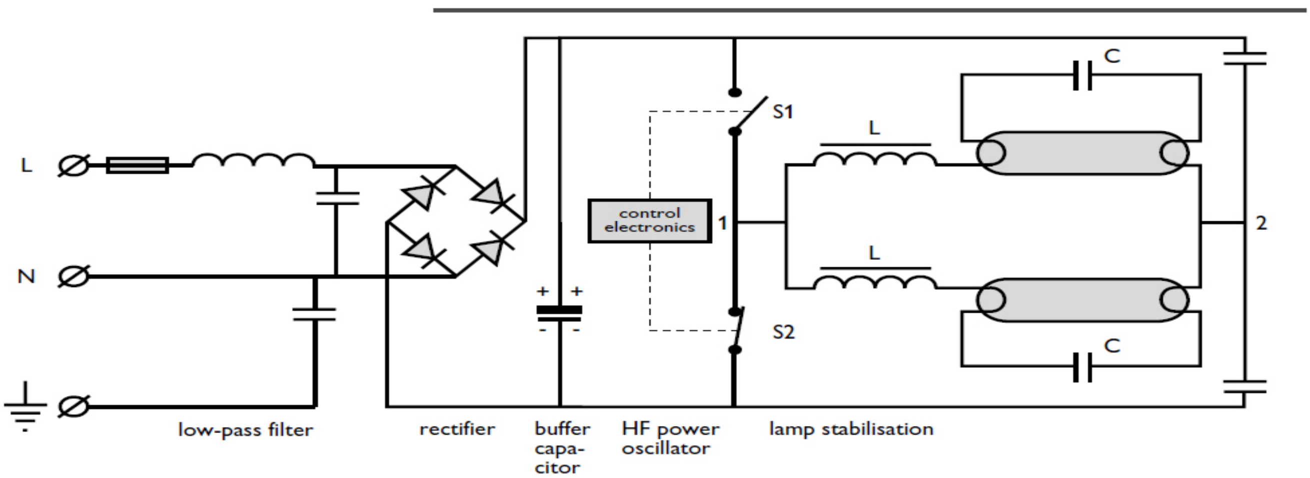


Fig. 44 Circuit diagram of an electronic control system (version with two lamps in parallel).

The low-pass filter has four functions:

- Limitation of the harmonic distortion, so that its level remains within international standards (see Fig. 45).
- Limitation of radio interference, which would otherwise be injected from the HF ballast into the mains. Here also international standards are to be adhered to.
- Protection of the electronic components against high mains voltage peaks.
- Inrush current limitation.

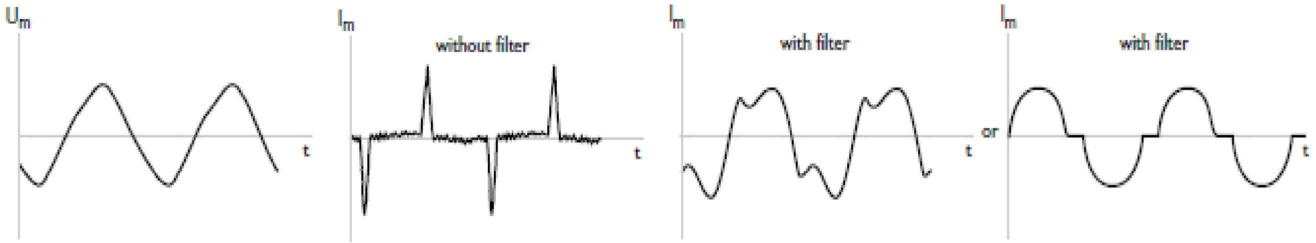


Fig. 45 Mains voltage and mains current, the latter without and with low-pass filter.

The low-pass filter is fully electronic . The different functions (lowpass filter, RFI suppression, inrush limiter and transient limiter) are separated (see Fig. 46).
The advantages of the fully electro-nic version compared with the older 'split' version with a separate filter coil, include: it is smaller, lighter, has a high power factor, the light output is independent of mains-voltage fluctuations, and there is no 50 Hz hum.

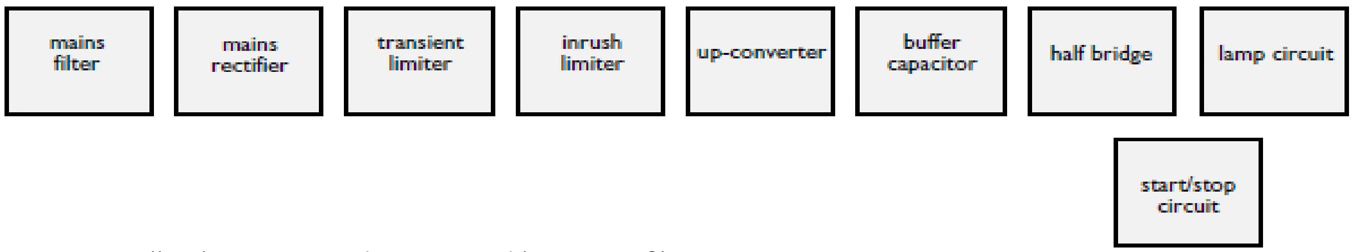


Fig. 46 Fully electronic and integrated low-pass filter.

The rectifier consists of a full diode bridge.The buffer capacitor in principle determines the shape of the lamp current and the mains current. It has to be chosen carefully in order to minimise the modulation in the lamp current (and thus the modulation in the light output). With a 'high' capacitor value the modulation in the light output is less than with a 'low' capacitor value, but the mains current waveform is more distorted (less sinusoidal), resulting in higher harmonic distortion (see Fig. 47). Furthermore, the level of the inrush current depends on the value of this buffer capacitor. The HF power oscillator is the heart of the electronic ballast. Controlled by the ballast controller the semiconductor switches S1 and S2 (Fig. 44) are switched at a frequency ranging from 30 to 100 kHz, so creating an HF square-wave voltage between the points 1 and 2. The frequency is regulated by the ballast controller. The controller contains all necessary sensors and intelligence to manage the mains input and lamp output functions of the electronic ballast, such as the preheating process, lamp power, stop circuit or safety switch-off,mains voltage fluctuations and mains frequency variations and sometimes over-voltage detection.

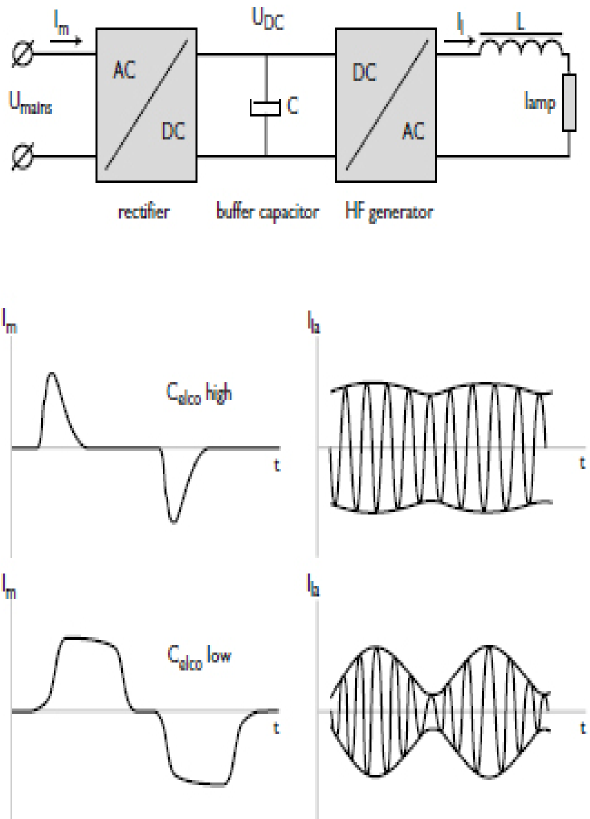


Fig. 47 Circuit with rectifier, energy buffer and HF generator. The curves show the lamp and mains current at high and low capacitance of the energy buffer for a typical CFL lamp.

The HF square-wave voltage is fed to the series connection of the lamp and the HF choke coil L (stabilisation coil). In the twin-lamp parallel version both lamp branches are connected in parallel with a choke coil for each lamp (Fig. 44). In the twin-lamp series version and in the single-lamp version, there is only one branch between the points 1 and 2 with one choke coil (see Fig. 48).

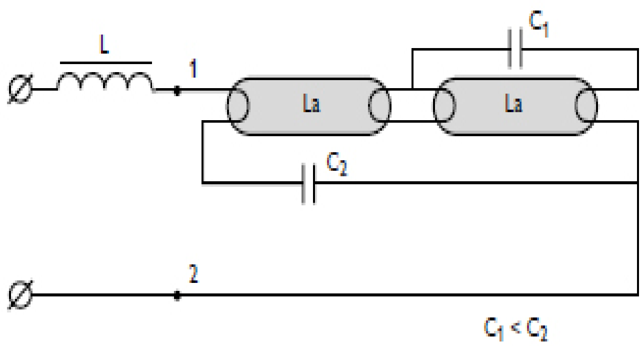


Fig. 48 Twin-lamp series version with only one branch between the points 1 and 2 with one choke coil.

Capacitors connected in parallel to the lamps are necessary for, among other things, the preheating and starting process: during preheating the current flows through the lamp electrodes and through these parallel capacitors.

Choice of frequency

As described the operating frequency should be above 10 kHz for 'T8 lamps to obtain 10 per cent more efficacy, compared with the 50 Hz operation, and above 20 kHz to be above the human threshold of audibility. On the other hand, it should be below approximately 100 kHz to limit the losses in the ferrite coils and transistors. Apart from these considerations there is a third factor to be considered: like all lamps, fluorescent lamps emit not only visible light, but also have a variable amount of infrared emission. Modulated in a high frequency, this can disturb infrared remote controls as used for televisionsets, audio, video, transmission systems and data communication.The lowest practical frequency for these systems is found in the RC5 system, working on 36 kHz. So the operating frequency for HF fluorescent lamps should not be 18 kHz or 36 kHz. Nowadays the frequency range from 30 kHz to 40 kHz is more or less reserved for IR systems. It is for this reason that various operating frequencies have been chosen for the newer generation of HF ballasts: an operating frequency of about 45 kHz was chosen for the new generation HF ballasts .

Ignition and re-ignition

As described a fluorescent lamp with cold cathodes needs up to an ignition peak voltage of more than 800 V r.m.s. depending on the lamp type, which means 1500 V top value. Due to this cold starting process emitter material will sputter away from the lamp electrodes. Frequent switching will thus result in a noticeably shorter lifetime.Another possibility is to bring the lamp electrodes up to their emission temperature before ignition by means of preheating.This is done by applying a frequency different from the operating frequency (normally higher) to the LC starting circuit for about 1.4 second to ensure a low open circuit voltage during the preheat phase (approx. 250 V) and a sufficiently high preheat current (see Figs 49).

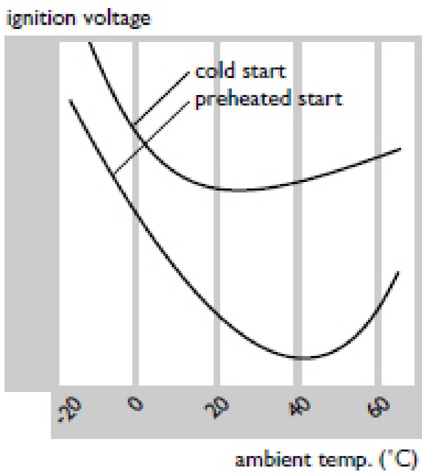


Fig. 49 Required ignition voltage as a function of the ambient temperature with preheated and non-preheated electrodes.

After the preheat time, a voltage of approx. 500 V (depending on the lamp type) is applied, again by changing the frequency, sufficient for reliable ignition during a maximum of approx. 0.2 second. The lamp ignites at the first ignition peaks and then the ignition voltage stops. After the preheat and ignition phase, the lamp gets its normal operating voltage (between approximately 50 V and 200 V, depending on the lamp type)

There are two ways of preheating:
- current preheating, with a more or less constant current through the cathodes
- voltage preheating, with a voltage depending on the actual working frequency (viz. dim level) where the cathode current is higher at lower dimming levels. Due to this warm start, the lifetime of the lamps is not so much dependent upon the switching cycle as compared with the cold start method and conventional gear. At the moment of ignition, the energy in the LC circuit is high enough to transfer the initial glow discharge into the stable burning discharge. After ignition the electronic ballast adopts its normal operating frequency. No extra voltage is necessary for re-ignition at this working frequency, as the plasma in the discharge remains conductive at this high frequency.

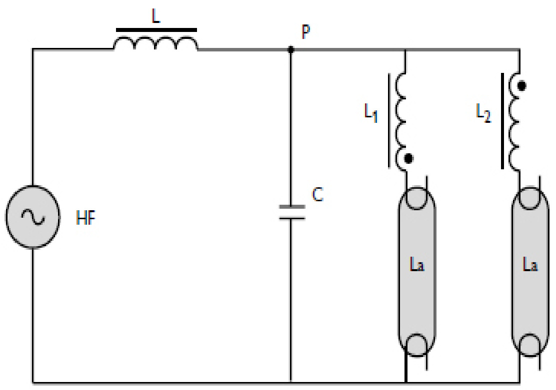


Fig. 51 Ignition with a twin-lamp HF ballast.

Ignition of a twin lamp ballast works on the same principle: in the preheat phase the voltage at point P (Fig. 51) is 300 V. In the ignition phase, this voltage will be 500 V, giving the required ignition voltage for both lamps. Once one lamp is ignited, the voltage at point P changes to 300 V, which is divided into 100 V for the lamp and 200 V for the transformer coil L1.

As transformer coil L2 is wound in the opposite direction, the open voltage for lamp 2 is still 300 + 200 = 500 V until the second lamp ignites as well. The run-up time of fluorescent lamps is very short, as the lamps get their nominal lamp voltage almost immediately. But with the amalgam lamps (CFL) it takes a few minutes before the amalgam is warmed up sufficiently to evaporate the amount of mercury necessary for the full light output. It can also take a few minutes for the lamp tube to reach its optimum temperature . All HF ballasts have an automatic stop circuit. Should a lamp fail to ignite at the first attempt (for example at the end of its lifetime), the electronics switch off the ballast after about 5 s. In this way, the so-called anomalous condition that can be found with starter circuits is avoided, resulting in:
- after the switch-off, system losses of only 1 W
- no annoying flashes of the non-starting lamp or heatingup of the lamp caps
- no unnecessary radio interference.

After having replaced the lamp, most ballasts are immediately ready for operation again and the lamp starts without having to reset the mains (switching the mains supply off and on again).This means that lamp replacement can be done while the mains power remains on.Although not recommended, this is often done in practice. Should the lamp extinguish as a result of an interruption or dip in the mains voltage, instant re-ignition is guaranteed as soon as the voltage returns. With the twin-lamp ballasts, the stop circuit switches off both lamps when one lamp fails or when either is not connected to the ballast. This is because the ballast control system is comparing both lamp currents and must them make them equal in stable operation. If one of the currents is zero after the ignition phase, the other will become zero as well.

Sometimes so-called 'independent lamp operation' is offered with twin-lamp ballasts.This feature suggests that if, in a twin-lamp system, one of the lamps should fail, the other one will continue to operate. However, with many such twin-ballasts this is only true as long as the system is not switched off. Once the mains is switched off, the intact lamp will fail to ignite at subsequent switch on. There are some special twin-ballasts available that do offer such independent operation, but these are also special as regards their (higher) price. In spite of this, this independent operation will be the trend for the future. Some HF four-lamp ballast contains two parallel circuits of two lamps. Should one lamp fail, the other lamp of the same branch will be switched, but the second branch will continue to work.

Cut-off principle

The cut-off principle minimises the current through the lamp electrodes shortly after the lamp is ignited. Not only does this save energy, it also lowers the temperature at the lamp ends.The standard T8 lamp is optimised for a tube wall temperature of 40 °C, which is reached at an ambient temperature in the luminaire of 200 to 25 °C. The cold spot is in the middle of the lamp (see Fig. 52).The T5, however, is developed to function in smaller luminaires at an higher wall temperature of 45 °C, which should be reached at an ambient temperature in the luminaire of 35 °C. The cold spot is at one end of the lamp.Without cut-off (see Fig. 53), this cold spot would become too warm, meaning that the lamp would function optimally at an ambient temperature of 27 °C. With cut-off (Fig. 53), the optimum is reached at an ambient temperature of 35 °C (see Fig. 54).

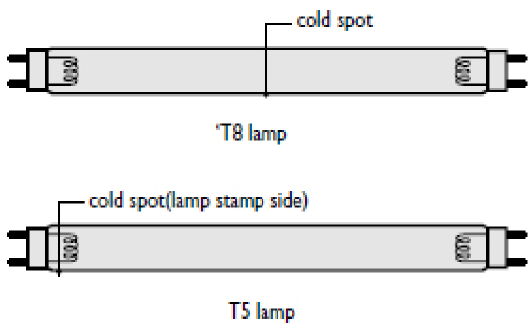


Fig. 52 Cold spot of T8 and T5 lamp.

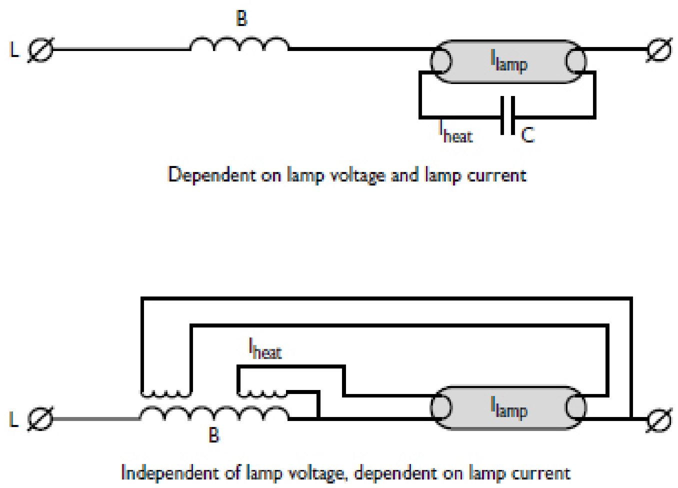


Fig. 53 Cut-off principle

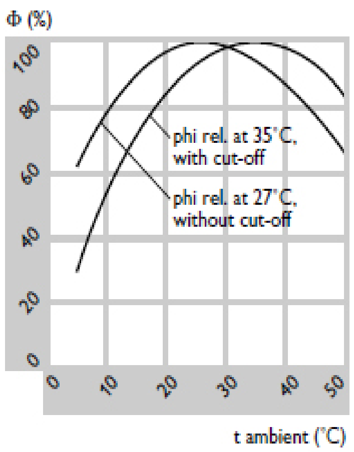


Fig. 54 Luminous flux with T5 and HF ballast with and without cut-off.

Harmonic distortion

Due to the rectification that takes place and the presence of a buffer capacitor, the mains current is temporarily zero and has a peak waveform (see Fig. 55).According to Fourier's law, the peak waveform can be split up in the fundamental and its higher harmonic components. The frequency spectrum can be measured by a spectrum analyser (see Fig. 56).Assuming the fundamental to be 100 per cent, the higher harmonics can be expressed as a percentage of the fundamental. International standards such as IEC 555-2 and EN 61000-3-2 restrict the amount of higher harmonics in the mains current for lamp circuits of more than 25 W.
For the example of the flourescent lamp the following results are obtained:

Harmonics		In,eff	In,eff/ I1,eff	IEC requirement
Number	Frequency (Hz)	(mA)	(%)	(%)
1	50	96	100	100
2	100	0	0	2
3	150	89	92	30 .λ
5	250	74	77	10
7	350	57	59	7
9	450	40	41	5
≥11	550	25	26	3

where λ = the power factor of the circuit.
Due to the circuitry, only the odd harmonics are present in the mains current.

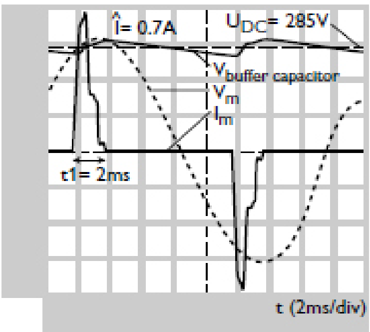


Fig. 55 Voltage and current shapes with a double-sided rectifier.

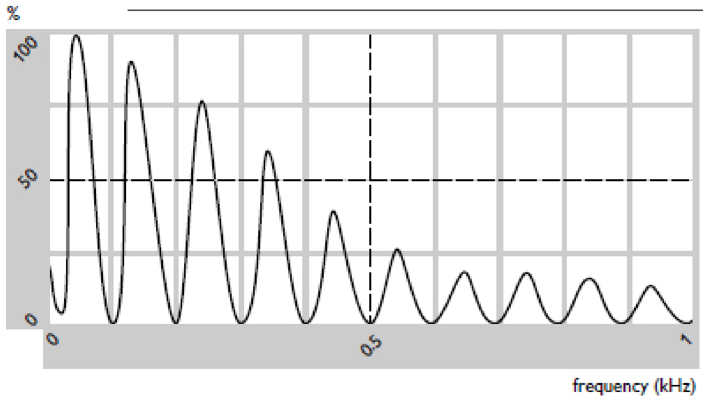


Fig. 56 Frequency spectrum of the mains current for a fluorescent lamp

Comparing the results with the requirements, it can be seen that the limits are exceeded.This is due to the absence of the mains filter. For the fluorescent lamp ballast , this is acceptable, as the total system power is less than 25 W. To adjust to the stated requirements for the maximum amount of higher harmonics, the circuit current has to be filtered.This can be achieved by a low-pass filter, which may consist either of a copper-iron coil or a fully electronic circuit. All good HF ballasts have such a low-pass filter and are therefore designed in accordance with the regulations laid down in the IEC standards. The electronic ballast system gives the following indicative values:

Harmonics	$I_{n\ eff} / I_{1\ eff}$ (%)		
Number	HF 128 TLD	HF 258 TLD	HF 258 TLD
1	100	100	100
3	7	6.5	10
5	2.5	2	2
7	2	2	2
9	1.5	1.5	1
≥ 11	1.5	1	1
THD (%)	8	7.5	12

In this case the harmonics are well within the limits.

The term THD (Total Harmonic Distortion) is defined as:

$$THD = \sqrt{\sum_{n=2}^{\infty} \left(\frac{I_n}{I_1}\right)^2} = \sqrt{\frac{I_2^2+I_3^2+I_4^2+...}{I_1^2}}$$

which means the root mean square of the sum of all the higher harmonics divided by the fundamental. It can be calculated from the values obtained by the spectrum analyser, and for the lamp example this value is 1.44 (= 144 %). Nowadays, even with very simple handheld instruments, this value can be measured very accurately. For compliance with the standards the measurements of the higher harmonics are made with a supply voltage with a THD maximum of 2 %. In practice, however, the THD of the supply voltage can be much higher.According to the EN standard 50160 "Voltage characteristics of electricity supplied by public distribution systems" of November 1999 the maximum permitted THD for the supply voltage is 8 % for 95 % of the time .

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative voltage (%)	Order h	Relative voltage (%)	Order h	Relative voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6-24	0.5
13	3	21	0.5		
17	2				
19-25	1.5				

This means that in practice the values for the harmonics in the supply current can be higher than the published values.The actual values then greatly depend on the harmonics present in the supply voltage. No problem should be expected when the THD of the supply voltage complies with the mentioned IEC 50160.

Power factor

In present-day publications the term power factor λ or P.F. is employed and 'cos φ' is no longer used. The phase angle between the fundamental wave of the mains voltage and the fundamental of the mains current is called φ.This angle can be calculated or measured, and in the case of HF ballast circuits is nearly zero degrees (see Fig. 57), so extra compensation with compensating capacitors, as is the case in the conventional circuits, is not necessary.

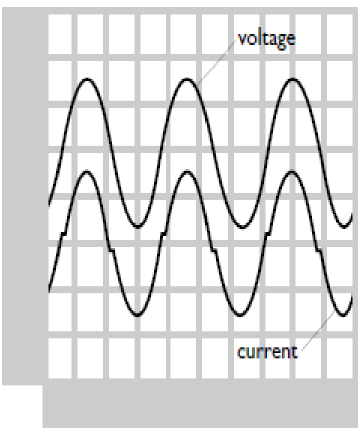


Fig. 57 The near-zero phase angle in an HF ballast circuit.

In practice, most supply voltage waveforms approach the sine wave shape rather well. In that case, the dissipated power is:

P = Ueff . I1,eff. cos φ

with I1,eff = the fundamental component of the mains current.
This means that the dissipated power is determined only by the fundamental of the mains current. Higher harmonics of the mains current do not play a role for the lamp and ballast power, but they do contribute to the power losses in the cabling and thus influence the minimum diameter of the cable needed in the electrical installation. If the mains voltage is not a pure sine wave, additional power will be dissipated in the lamp and the ballast. In practice, the cosine of the angle φ is between 1 and 0.93 capacitive for HF lamp circuits.mThe power factor of the circuit is the quotient of the actual consumed power and the product of the values of the mains voltage and mains current (r.m.s. values):
P.F. or λ = total wattage / mains voltage x mains current.
With RMS equipment these values can be measured very well.

The power factor is determined by:
- the phase angle φ
- the distortion of mains voltage and mains current.

If the mains voltage has a good sine wave (little or no distortion), the power factor will depend only on the harmonics in the mains current, according to the following formula:

P.F. = cos φ / $\sqrt{}$[1 + THD2]

where THD stands for Total Harmonic Distortion of the mains current .This means that circuits having a different cos j can have the same power factor:
1. In a conventional circuit without parallel compensation the mains current is virtually sinusoidal (THD = 0.1), but the phase shift between mains voltage and mains current is about 60 electrical degrees , resulting in cos φ = 0.5 and a power factor of 0.5.
2. In the electronic circuit the phase shift is nearly zero (cos φ = 1), but there are a lot of harmonics in the mains current, giving a THD value of about 1.44 (or 144 per cent), which results in a power factor of 0.57.

The energy suppliers have to deliver to the circuit an apparent power of:
S = Vmains . Imains
but they only get paid for the average power
P = λ .Vmains . Imains.

The electrical distribution system (cabling, transformers) must be capable of handling a current of Imains instead of a current of Imains . P.F. This calls for thicker cabling and heavier transformers and introduces higher distribution losses.The supply authorities therefore demand compensation of the phase shift and limitation of the harmonic distortion by requiring a power factor of 0.85 or more for lamp circuit powers of 25 W and more.The power factor of H.F. ballasts is >0.95 , but leading.

Inrush current

The current that flows during the very first few milliseconds when switching on a luminaire or an entire lighting installation is called the inrush current. This current is very important when making the right choice of switchgear and fusing, e.g. circuit breakers. The inrush current is determined in part by the circuitry in use and in part by the properties of the mains supply, viz. the mains-supply impedance and the supply-cable resistance.The moment of switching in relation to the sine wave of the supply voltage also determines the value of the inrush current.The highest inrush current is when the ballast is connected to the mains at the peak of the mains voltage.

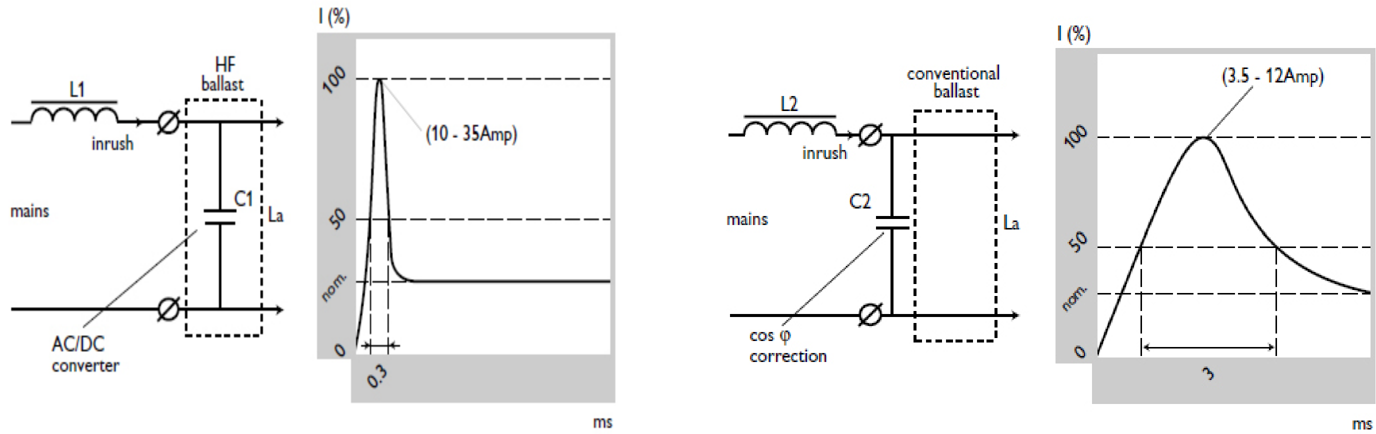


Fig. 58 The inrush current of an HF ballast compared with that of a conventional ballast.

With the introduction of HF ballast systems the effect of the inrush current became more important. There are two reasons for this:

1. Due to the electronics employed, more HF ballasts will switch on at the same instant, which adds to the value of the individual inrush currents to be supplied by the mains. Conventional ballasts switch on at random, avoiding this phenomenon.
2. For the same lamp wattage, the inrush-current pulse of an HF ballast is in principle higher and narrower than that of a conventional ballast (see Fig. 58).With an HF ballast, the inrush current loads the buffer capacitor C1, while in the conventional case the parallel compensating capacitor C2 is loaded. The value of C2 is lower than that of C1, which explains the trend of the currents. Compare, for example, the values for a 36 W T8 lamp: conventional C2 = 3.6 μF, HF ballast C1 = 10 μF.

For the typical current/time curves of Fig. 58 we assume that the inductance of L1 equals that of L2.As a result, the I2t value of HF ballasts is higher than with conventional ballasts. The inrush current can trigger Mains Circuit Breakers (MCBs), fuses or relays (as used in control systems) when the inrush currents peak in the hatched part of Fig. 59. According to the graphs, the maximum current of relay contacts is lower than that of MCBs (where the inrush current is sensed by a coil).When the coil of an MCB trips because the inrush current exceeds a maximum level, the main contacts (which are normally quite heavy,since they are so constructed as to be capable of switching off the current caused by short-circuiting) switch off, which explains the different behaviour with respect to normal relays.

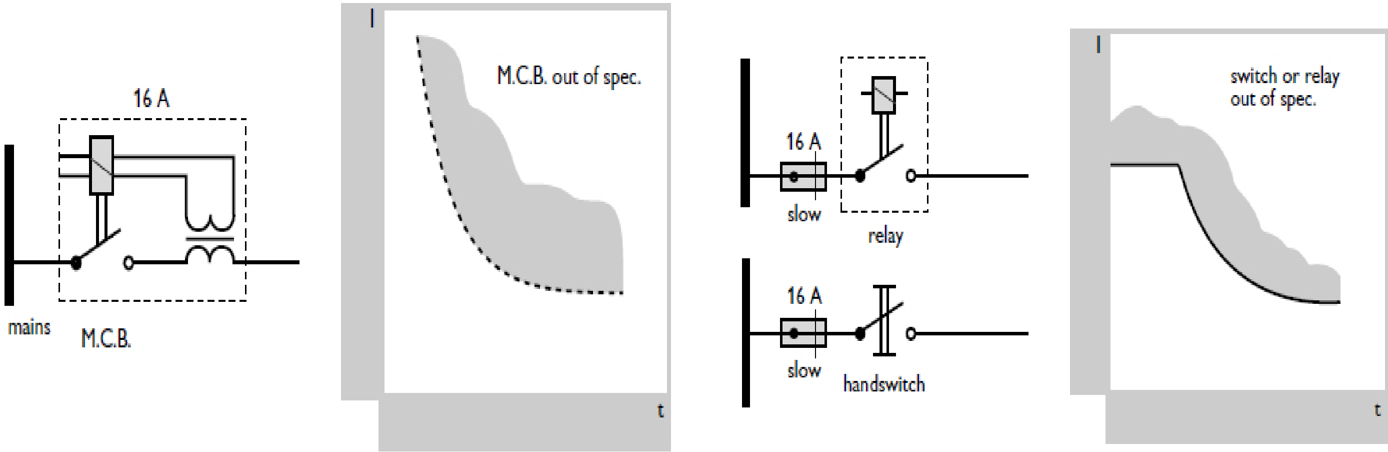


Fig. 59 Inrush currents may trigger MCBs, fuses or relays when they peak in the hatched part of the curves.

With the fully-electronic filter, the maximum inrush current is reached when the mains voltage is at its maximum value at the moment of switching on.The maximum value can be as much as 200 times the nominal mains current value, depending on the properties of the mains and RFI filter . Details for the various ballast types can be found in the product data sheets .

Circuit breakers and fusing

The main purpose of protection devices such as mains or micro circuit breakers (MCBs) and fuses is to protect the cabling and the distribution part of the lighting installation from damage in the case of a failure or overload in the system.The rating of the protection devices is therefore primarily related to the cable core used in the installation, following the various national and international safety standards. In lighting installations, the commonly used MCBs and fuses have a rating of 10 A or 16 A. It will be evident that a 16 A device can handle a 1.6 higher load than can a 10 A device. To prevent undesirable tripping of the MCB or the fuse from blowing, two criteria normally have to be taken into account:
- the maximum current during switching on or off in the part of the lighting installation that is protected by the MCB or fuse,
- the total nominal operating current during stable operation.

Also, in multi-lamp luminaires, the hot wires should be of equal length to avoid variation in lumen output between the lamps.The hot points are not marked on the ballast separately, but they can easily be found: on the ballast connection diagram the hot points are those terminals that have the shortest lamp wiring drawn. Correct wiring is essential for correct functioning. Installation rules in most countries do not permit the routing of mains wiring and other wiring (e.g. control wiring, telecommunication wiring) together in the same cable ducts.The main reasons for this are the need to obtain optimum safety and to prevent disturbances and faulty connections.

Lifetime

The overall lifetime of an electronic ballast is determined by the lifetime of each individual component employed in the ballast and the effect of voltage, current and temperature occurring.The lifetime of an individual component is mainly dependent upon the quality of the material employed in manufacture and the manufacturing process. Usually, each component is checked not only for proper functioning immediately after manufacture, but also in use.Typical for electronic components is that if they have defects, these will show up in the early hours of operation. After this so-called burn-in period failures will only very seldom occur. Professional electronic ballasts undergo a burn-in period for a specified period before leaving the factory.The purpose of this is to reduce the chances of early failures in an installation as much as possible. In order to control the failure rate of a complete ballast, the method of calculating the Mean Time Between Failures (MTBF) is adopted.This takes into account the MTBF of all the individual components.The failure rate is divided by the MTBF. Since the maximum temperature within a luminaire is very important for the lifetime of a ballast, the calculations are normally based on a temperature of 65 °C at a defined spot on the ballast enclosure. The quality of the design and of the components must result in a certain specified calculated failure rate. For most electronic ballasts this is set to 1 per cent at 5000 hours.
According to the equation:

$R_t = e^{-\lambda t}$ or $\ln R_t = -\lambda t$

where Rt = remaining ballasts after the time t, and λ = the failure rate 1 %/5000h = 0.20 .10-5 , it is found that 36.7 per cent of the ballasts are still operational after 500 000 h, or 50 per cent after 346 000 h. The 10 per cent failure rate is reached after 52 680 h. The temperature dependence of the failure rate can also be calculated.
For most electronic ballasts this gives the following figures:

Test-point temperature (°C)	Failure rate (% per 1000h)		
	HF	HF cold start	low end HF
55	0.15	0.20	0.30
65	0.20	0.28	0.40
75	0.30	0.43	0.60

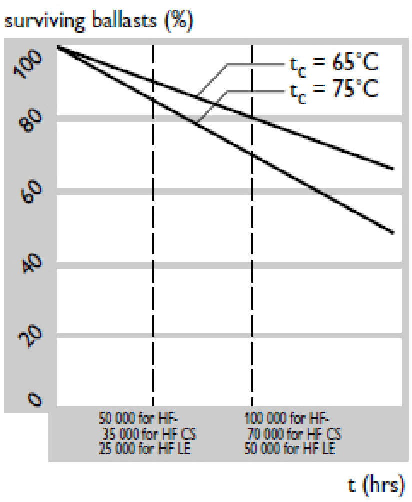


Fig. 64 Mean Time Between Failures (MTBF).

These calculated figures are verified by lifetime tests for the various ballasts (see Fig. 64).

One of the reasons for the increase in the failure rate at higher temperatures is the temperature dependency of capacitors employed, especially the electrolytic buffer capacitor. In order to verify the outcome of calculations, lifetime tests are continuously carried out on batches of ballasts. It is found that during a long period after the burn-in period the lifetime of the ballasts is in accordance with the calculated failure rate. But after this long period, the failure rate then increases very rapidly, ultimately resulting in the end of the lifetime of the batch of ballasts (see Fig. 65).

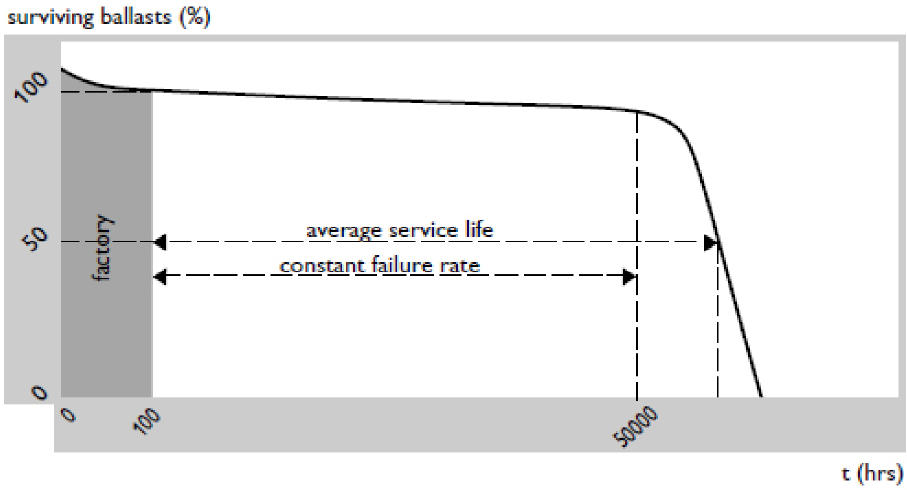


Fig. 65 Lifetime curve of electronic ballasts, showing rapidly increasing failure rate after a certain period.

There are two major reasons for this phenomenon: drying up of the liquid of the electrolytic capacitors, and degradation of the soldered contacts. The soldered contacts are specified to have a lifetime of 2500 to 3000 switches in the temperature-change test of -20 ° to +100 °C.This wide temperature range of 120 degrees will not be found in practice; temperatures between + 20 ° and + 60 °C (a range of 40 degrees) are more likely.

The actual switching lifetime can be calculated from the following equation:
$N_{switch} = 2500 \times (120 / \text{practical temperature range})^2$.

So in the example:
$N = 2500 \times (120/40)^2 = 2500 \cdot 9 = 22\,500$ times.
Supposing the average burning time of the fluorescent lamps is 2 hours, this would result in a lifetime of the complete ballast of 2 x 22500 = 45 000 hours.

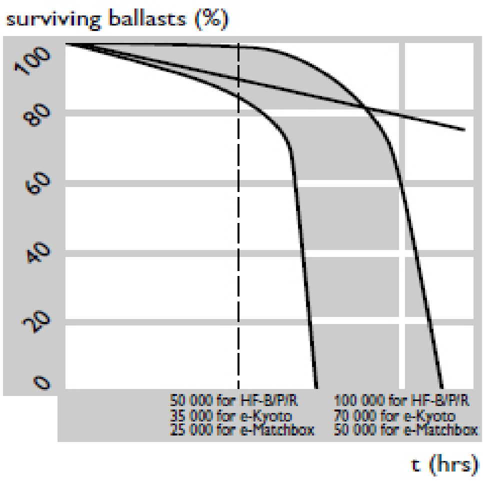


Fig. 66 Total of failure mechanisms.

The time after which 50 per cent of the ballasts have failed is called the average service lifetime. For most ballasts in normal operation, this average lifetime is approximately 50 000 h at a fixed specified case temperature (65 °C).A temperature increase of 10 degrees halves this average service lifetime (thus, 75 °C gives 25 000 h), while 10 degrees lower doubles this figure (55 °C gives 100 000 h).Taking into account the various tolerances and spreading results in Fig. 66.

Effects of mains voltage fluctuations

The mains voltage to which a luminaire is connected is never constant; it is influenced, for example, by the switching on and off of other loads.Therefore, the voltage level can only be guaranteed between minimum and maximum tolerances. Moreover, the nominal voltage can differ from country to country. In the UK, for example, the nominal voltage is 240 V compared with 230 V for the rest of Western Europe. The nominal operating voltage of a ballast can be found in the product data sheets. It may be a fixed value, as is the case with conventional ballasts. With respect to voltage fluctuations, there are two requirements:
1. A general safety requirement. No unsafe situation should occur within the range V nominal ± 10 % (in this regard attention should, for example, be paid to lifetime, temperatures, voltages).
2. A performance requirement.The circuit must perform within specified limits within the range V nominal - 8 % to + 6 % (in this regard attention should, for example, be paid to lumen output, currents, (re-) ignition).

And, again with respect to voltage fluctuations, the electronic ballasts can be divided in two groups:
1. A group in which the circuit power, lumen output, lamp current, etc. vary noticeably with fluctuations in the mains voltage .

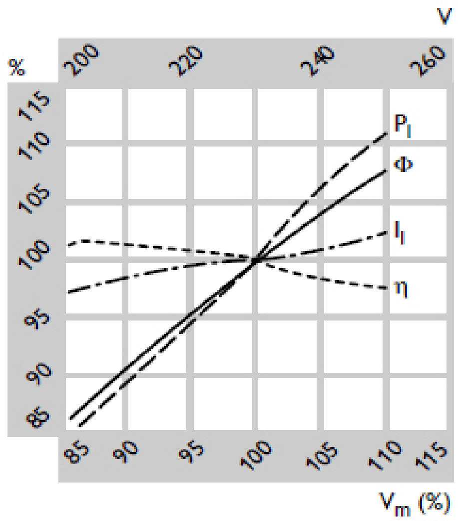


Fig. 67 Considerable influence of mains-voltage fluctuations on lamp power (Pl), luminous flux (Φ), efficacy (η) and lamp current (Il)

2. A group based on the independent mains principle, where the lamp power and lumen output hardly
change with variations in the mains voltage (see Fig. 68). It must be kept in mind that with the independent mains principle (sometimes also called constant-wattage) the mains current will rise with decrease in mains voltage.

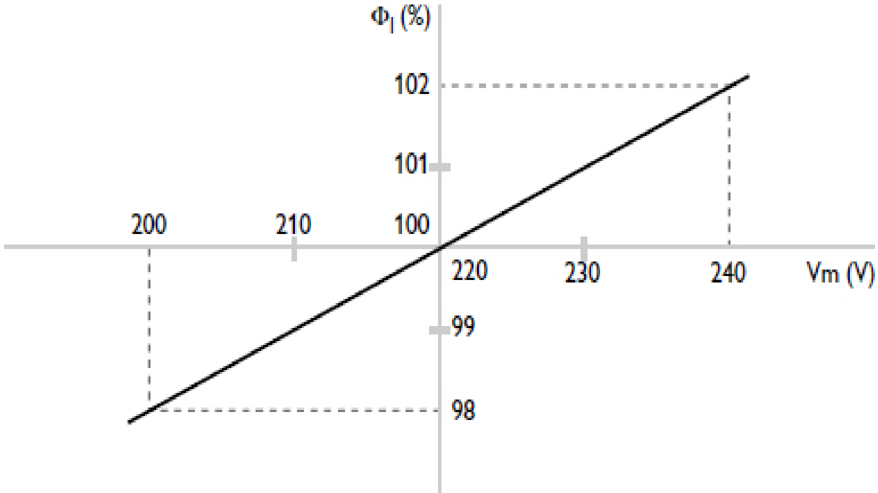


Fig. 68 Constant-wattage ballasts (e.g. HF-R). For a given mains voltage variation between 200 V and 240 V, the light output remains constant (tolerance ± 2 %).

All ballasts can withstand a certain over-voltage for a specified time, for example 380 V for 5 minutes. See for this point the product data sheets. Moreover, some electronic ballasts have an over-voltage detection.When the mains voltage rises above a certain value (usually 280 V r.m.s.), perhaps, due to a fault in the installation or a mistake in a testing procedure, the lamps are switched off.This switch-off feature provides a clear indication that the installation is not functioning properly and that corrective action is necessary.The lamps remain off until the unduly high mains voltage is corrected and the ballast is reset. Resetting must be done by switching off the mains supply to the ballast. After the ballast has switched off the lamps (in case of over-voltage), the high mains voltage is still connected to the input circuit. It is therefore essential that corrective action be taken immediately.

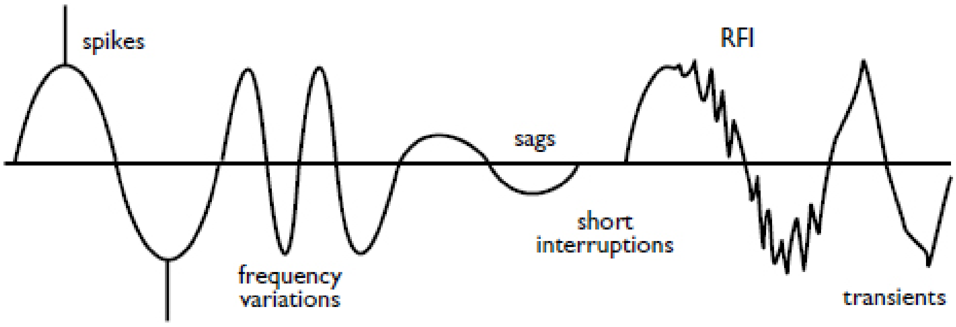


Fig. 69 Different types of mains-voltage disturbances.

Transients and dips

The mains supply voltage can be disturbed in many ways, see Figs 69 and 70.
Disturbances of short duration, especially, can cause an interruption of the light output. Example, quoted from IEC 1000-2-2:5:
'At present as an approximate guide, it can be stated that an individual consumer in a town may suffer on average one to four times a month from voltage dips which exceed 10 % of the nominal supply voltage and which are due to causes outside his premises.The duration of these voltage dips is usually between 60 ms and 3 s, but durations of around 10 ms are possible mainly when faults are eliminated by fuses.'In rural areas, generally supplied by overhead lines, the voltage dips are much more frequent, but no useful estimates of the rates of occurrence of such dips are available.

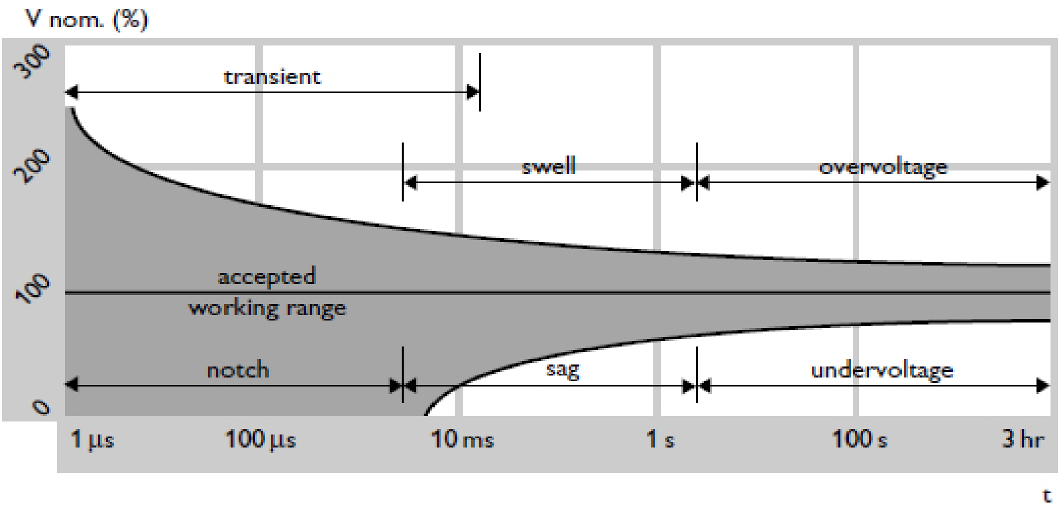


Fig. 70 Effects and duration of mains-voltage deviations.

Peaks or transients can also damage the electronic ballast.There are several old, new or revised recommendations and standards covering this subject.To comply with the latest norms, Good ballasts are, or will be, designed according to the latest norm IEC 1547 (draft): Equipment for general lighting purposes - EMC immunity requirements. This ensures a very good immunity to the most common mains-supply distortions.

Ambient and operating temperatures

The behaviour of the total lighting system (viz. lamp, ballast, luminaire, wiring, mounting and supply voltage) with change in temperature is mainly based on the temperature of the lamp in the actual situation. In general, the specifications of electrical components are not valid under -15 °C/ -25 °C, so below these temperatures there is no guarantee for proper functioning of the ballasts.
The ambient temperature range for the HF ballasts in the compact lamps is from -20 ° to +55 °C. Mounted in a luminaire, the hottest spot should be below 100 °C The ambient temperature range of 'T8' and PL-L HF ballasts is indicated on the ballast with the letter ta and ranges from -15 °/200 to + 50 °/70 °C. Due to the low watt losses in the HF ballasts, the temperature rise Δt of the ballast itself is limited to a maximum of approximately 15 degrees. Exceptions are, however, possible. An electronic ballast is usually built into a luminaire, so the ambient temperature around the ballast cannot be predicted exactly.A test point, tc , is therefore defined on the outside of the ballast enclosure, for which a maximum permitted temperature is specified for. This is normally 75 °C.The test point will reach this temperature when the ambient temperature around the ballast is 50 °-60 °C, depending on the type of ballast. As long as the temperature of the test point remains below the specified maximum, the components will not be subjected to temperature overload.
The tc value is built up as follows:
Room temperature (e.g. 25 °C) plus temperature rise in the luminaire (e.g. 25 °C) equals ambient temperature for the ballast (50 °C in this case).Ambient temperature plus temperature rise of the ballast itself (e.g. 15 °C) gives tc = 50 ° + 15 ° = 65 °C.
From this it follows that the room temperature directly influences the test-point temperature.The temperature rise of the air in the luminaire has to be measured. Variations of 15 °C between a completely closed plastics luminaire and an open (bare lamp) metal luminaire are possible. Also, the distance from the ceiling influences the cooling properties of a luminaire, for example:

Distance to ceiling (cm)	0	1.25	2.5	5	10	15
Temperature drop (K)	0	1.5	6	14	20	22.5

As the enclosures of the electronic devices are often made of thin metal or some type of plastics, the measurement of the temperature at the test point must be done very carefully.The use of a rather large test finger, as supplied with some multimeters, will undoubtedly indicate temperatures that are too low. Measurements must be made by means of thermocouples, which must be firmly glued to the surface (and not, for instance, with adhesive tape). The most common application of fluorescent ballasts is in indoor installations.When employed in outdoor installations, the luminaire must be of the closed type, minimum classification IP54. In cold situations, especially, striation may occur. In order to avoid the negative influence of humidity on ballast components and metal connections, special lacquered ballasts are available.

Besides the standard range of HF ballasts, a range of dimmable fluorescent ballasts that allow for the adjustment of lighting levels to suit personal preferences whilst at the same time providing the opportunity for additional savings on energy. Compared with the standard HF ballast, an additional light regulation circuit is incorporated, that varies the operation frequency for the lamps, according to the regulating input voltage (see Fig. 78).The control voltage is supplied to the connections '+' and '–' at the HF ballast and to the connections 'DA' for the HF- DALI (Digital Addressable Lighting Interface) version.

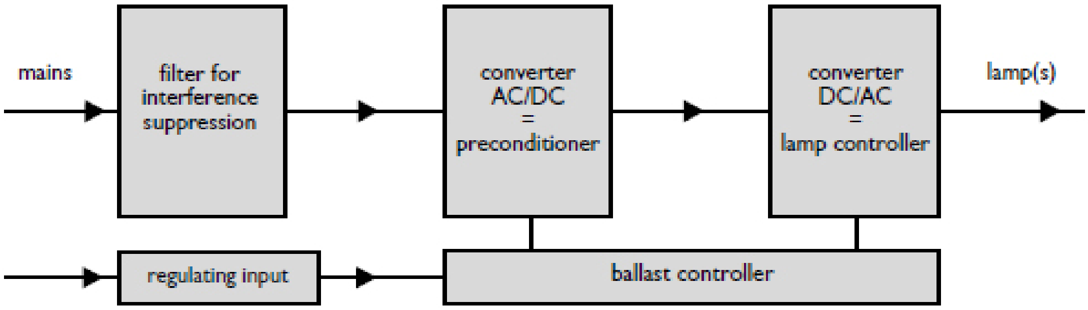


Fig. 78 Block diagram for an HF regulation ballast.

Operating switches S1 and S2 (see Fig. 79) at a higher frequency results in a lower lamp current, and so the light output decreases.

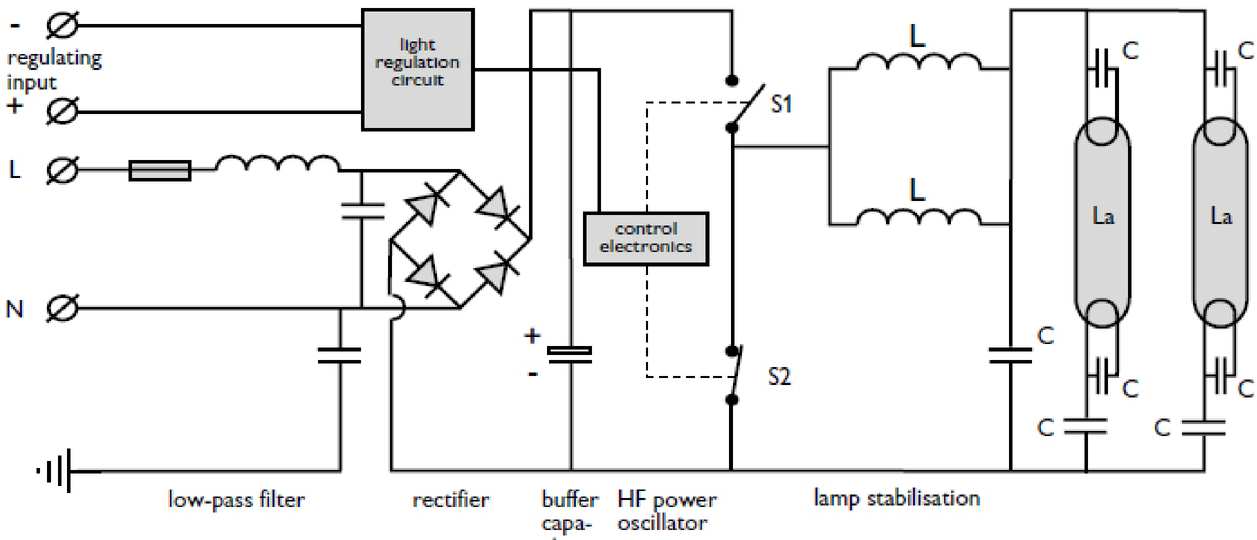


Fig. 79 General circuit diagram of an HF ballast for light regulation.

There are nowadays two ways to supply the control voltage to the regulating ballast, namely analogue and digital.The most common is analogue in which the input voltage for the light regulation circuit may vary from 0 V to 10 V DC: 1 V results in a minimum lighting level and 10 V in a maximum lighting level. In addition to the analogue dim input, a digital dim input is used in the DALI ballast.
The major European ballast and controls manufacturers support both of these systems, which guarantees compatibility between the various controls and ballasts.

The dimming process

The nominal operating frequency of the HF ballasts is around 48 kHz.At this frequency the lamp reaches its nominal 100 % operating values.The ballast controller can, activated by the light regulation circuit, vary the operating frequency between 48 kHz and 90 kHz. Basically, the regulating process can be understood as follows:At higher operating frequencies the impedance of the lamp current stabilisation coil L increases, resulting in a lower current .At the same time, the impedance of the capacitor C across the lamp decreases (capacitor impedance = $1/\omega C$, with $\omega = 2\pi f$).
The electrode current is a prerequisite for stable regulation of the lamps. Operating switches S1 and S2 (see Fig. 79) at a higher frequency results in a lower lamp current, and so the light output decreases. The electronic regulating ballasts contain more complicated circuits to optimise these currents within the operating area, with the lowest possible power.

H.I.D. Lighting Information

SOLOLUCE
ITALY

High Intensity Discharge (HID) Lamps

Range

The first discharge lamp Low Pressure Sodium lamp , introduced in 1932, was for an installation for street lighting. Nowadays a broad range of HID lamps is used in almost all applications, not only in sport stadiums, along highways, as urban lighting or to light large areas, but also in shops, museums, theatres and even in homes. Discharge lamps work on the principle that part of the energy released during the discharge through a gas is used to generate light.This happens in the discharge tube with sealed in electrodes, and filled with one or more metals and a starting gas, see fig.3. A voltage applied to the electrodes affects the free electrons in the gas, which start moving towards the positive pole. In doing so, they collide with the atoms in the gas.This results in heat development, electromagnetic radiation and ionisation.The electromagnetic radiation is of specific wavelengths, depending on the metals employed. Part of this radiation is visible light right away, whilst another part, in the ultraviolet range, may subsequently be converted into visible light by means of a fluorescent layer on the inner wall of the lamp.

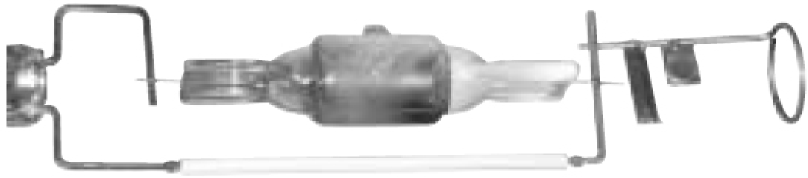


Fig. 3. Discharge tube of an HID lamp.

The starting behaviour of individual lamp

1. High-pressure mercury lamps

Fig. 8. High-pressure mercury lamp.

Fig. 8. High-pressure mercury lamp.

The combination of the gas filling, electrode emitter and auxiliary electrodes makes the lamps start on normal mains supply voltage; there is no need for an ignitor. There is a relationship between minimum supply voltage and ambient temperature. For example: at 20°C ambient temperature a supply voltage of 180 V will ignite the lamp, while at -18°C a minimum supply voltage of 210 V is needed for proper ignition. There are no special requirements for wiring or cabling. The re-ignition time is a maximum of 10 minutes. Immediate hot re-ignition is not possible (Edison fitting). The run-up time is approximately 5 minutes. The coating on the outer bulb is a fluorescent layer for converting the UV into visible light. Because of high lamp-voltage, the lamp only can be dimmed with the risk of extinguishing.

2. High-pressure sodium lamps

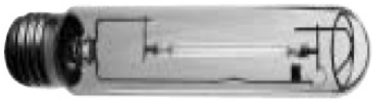


Fig. 9. High-pressure sodium lamp.

Fig. 9. High-pressure sodium lamp.

To start Sodium elliptical and Sodium Tubular lamps properly, a starting voltage is required that has to be not only sufficiently high, but its peak must also have the right shape with a certain rise-time and pulse-width. Sodium 70 W-I lamps have an internal starter with a bi-metal strip, which has to cool down after extinction. Their re-ignition time is therefore approximately 15 minutes. All other SON lamp types have a re-ignition time of 2 to 3 minutes and a run-up time of approx. 5 minutes.

Fig. 10.White SON lamp.

Fig. 10.White SON lamp.

The SDW-T lamp types run up in 2 minutes and the re-ignition time is 1 minute with the CSLS control unit. The coating on the outer bulb is to spread the concentrated light from the relatively small discharge tube over the much greater surface of the outer bulb. The SON lamps produce hardly any UV. Lamps can be dimmed to 50% power with conventional gear and to 35% with appropriate electronic gear.

3. Metal halide lamps

Fig. 11. Metal halide lamp.

Fig. 11. Metal halide lamp.

The starting peak for proper ignition of Metal halide lamps lamps does not have the same shape as that for sodium lamps. As the maximum ignition voltage peaks are under 1000 V (except for the 2 kW/380 V system, where Vmax = 1500 V) there are no special requirements for cabling or wiring.
The re-ignition time of metal halide lamps is 15-20 minutes maximum and, due to the use of Edison lamp bases and holders, immediate hot re-ignition is not possible.

Fig. 12. Double-ended metal halide lamp.

Fig. 12. Double-ended metal halide lamp.

Double-ended metal halide lamps, such as the MHD-LA and SA types, are suitable for hot restrike with devices producing 35 kV to 50 kV. It must be ensured, of course, that the applied luminaire is also released for hot restrike. To ensure proper ignition of tthese lamp types, higher starting voltages are needed than with the E40 metal halide types.The re-ignition time of these lamps is between 10 and 15 minutes. All metal halide lamps mentioned have a run-up time of between 3 and 5 minutes. Because of negative effects on colour-shift, maintenance and lamp life these lamp-types cannot be dimmed.

4. Low-pressure sodium lamps

Fig. 13. Low-pressure sodium lamp.

Fig. 13. Low-pressure sodium lamp.

For low-pressure sodium lamps in particular, the right choice of circuit components is very important for the starting and run-up phase.With the standard circuits all lamps run up in about 12 minutes and they restrike immediately, with the exception of the SOX 180 W and SOX-E 131, which restrike after 10 minutes.The required pulse height for proper ignition is between 1000 and 1400 V, but more important is that the circuit delivers enough energy to pass through the run-up phase. It is not only the luminous flux and colour characteristics that change during the run-up period: the same happens to the lamp voltage and current. In most lamps the lamp voltage increases and the lamp current decreases during the run-up period.This is due to the pressure build-up a result of the increasing gas temperature (Fig. 14).

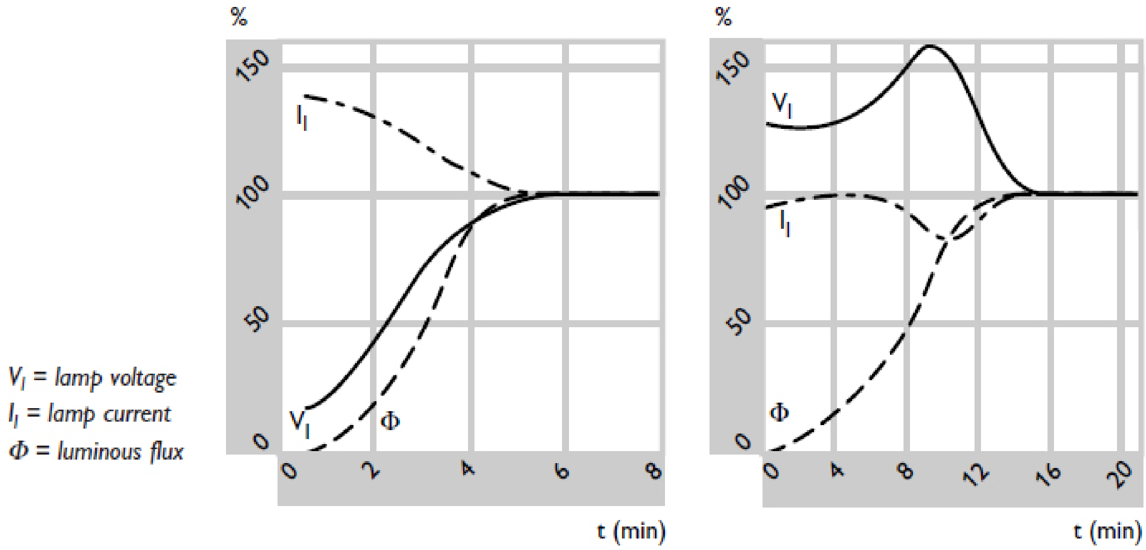


Fig. 14. Comparison between the run-up characteristics of a high-pressure mercury lamp (left) and a low-pressure sodium lamp (right).

In low-pressure sodium lamps and some fluorescent lamps, however, the opposite is true, which can be explained by the change in the composition of the filling gas as a result of vaporisation (see Fig. 14). SOX lamps cannot be dimmed.

HID Lamp behaviour as function of the frequency

HID lamps do not properly function on DC (Direct Current).This is due to the one side emission of the electrodes and the de-mixing of the gas. Practically all HID lamps are developed for conventional gear on a 50 or 60 Hz mains supply. Electromagnetic and hybrid solutions (conventional gear in combination with electronics) work on these frequencies. Low-frequency square-wave electronic HID ballasts operate on a frequency between 70 and 400 Hz, which prevents flickering. Fully electronic ballasts for HID lamps are becoming available with higher operating frequencies (10-500 kHz). The frequency and waveform of an electronic ballast cannot be chosen freely, but are dependent on lamp type, condition and temperature.A wrong choice of frequency and/or waveform can have a very negative effect on lamp performance and/or lifetime. Laboratory experiments have shown that the different types of HID lamps can only be stabilised at certain frequency bands. Outside these restricted bands, not only may the efficiency may drop, but the discharge tube may be mechanically damaged by acoustic resonance, or electrodes may break off. Electronic gear units are therefore only suitable for specified lamp types. Conversely, some HID lamps can only be operated on their electronic gear since there is no conventional alternative. The sorts of benefits obtained with fluorescent lamps (26-34 kHz) are difficult to achieve.

Lamp and system efficiency

Lamp efficiency is expressed in a figure called the luminous efficacy. It indicates the efficiency of the lamp in transforming electrical energy into light and is expressed in lumens per watt (lm/W). The amount of light generated by a lamp is called its luminous flux or lumen output. It is a variable figure, depending on many factors. In all documentation, the published figure is the nominal luminous flux, which is the lamp flux under the following conditions:

- the lamp has already burned for 100 hours (burning-in period) prior to measurement,
- the lamp is burning in free air,
- after switching on, the lamp has had sufficient time to heat up and stabilise for thermal equilibrium,
- the lamp is running at its nominal voltage, nominal current, rated ambient temperature, defined burning position and stabilised nominal mains voltage,
- the nominal luminous flux is based on the average value obtained from a batch of lamps.

The instant one of these conditions changes, the nominal flux changes with it.
Lamp types are indicated with a nominal wattage.This is not always the power actually dissipated in the lamp. The luminous efficacy is calculated by dividing the nominal lumen output by the actual power dissipated. The luminous efficacy of all HID lamps increases with the lamp wattage.This is because the power needed to keep the lamp electrodes at optimum temperature is relatively less for higher lamp wattages. For example, for mercury it varies from 36 lm/W for the 50 W type to 59 lm/W for the 1 kW type.

As the published figures for the lamps do not include circuit losses, the efficacy figures for the total system are lower. The figures published are for lamps stabilised by the electromagnetic circuits.With electronic gear there is a limited increase of efficacy.

The main part of the energy is converted into heat. A relatively small part is converted into visible light, (see Fig. 15).

1. power in discharge column - 376 W
2. thermal losses at electrodes - 24 W
3. visible radiation - 118 W
4. UV radiation from discharge column - 2 W
5. IR radiation from discharge column - 80 W
6. thermal losses in discharge column - 176 W
7. UV radiation - 1 W
8. IR radiation - 1 W
9. total IR radiation - 221 W
10. convection and conduction - 60 W

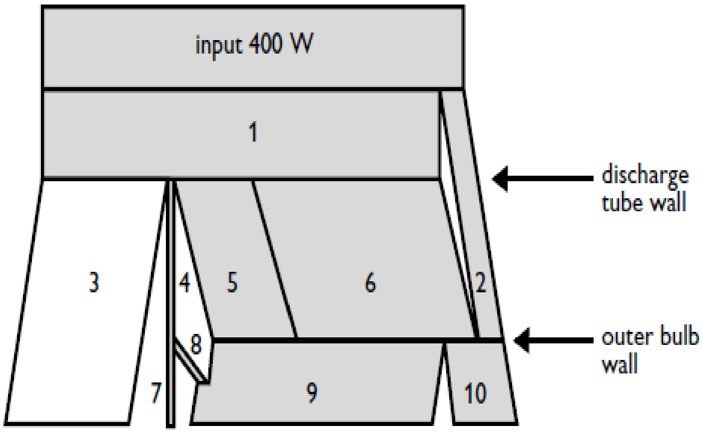


Fig. 15. Energy balance of an Sodium tubular 400 W lamp.

Effects of temperature

Low temperatures

Although the temperature of the discharge is of prime importance for the operation of discharge lamps, high-intensity gas-discharge (HID) lamps are not very sensitive to changes in the ambient temperature. There are two major reasons for this:

1.The discharge tube of most lamp types is enclosed in an outer lamp bulb and most of the HID lamps in floodlighting and other outdoor applications are placed in an enclosed luminaire, so that there is no direct contact between the outside air and the gas-discharge tube.

2. HID lamps operate at fairly high discharge-tub temperatures, so that the changes in ambient temperature are relatively small, compared with the actual burner temperature of a working HID lamp. Provided they are operated on the correct ballast and ignitor, all HID lamps will ignite at temperatures down to -20°C, while some types will even ignite at -40°C. SON and SOX lamps even will function without difficulty at temperatures down to -50°C.The only exception is the mercury lamp: the mercury gas pressure of which is more sensitive to low temperatures. Due to the electronic components, the permitted temperature range for the ignitors is from -20°C to +80°C. Also the compensating capacitors are mostly limited to -25°C. In practice there is not much difference in light output within the normal ambient temperature range of -20 to +40°C during stable operation. Of course the run-up time (time to reach a certain light output) can be longer at lower temperatures. High temperatures For all lamps there are two critical values, which are mentioned in the lamp specification:

1. The maximum permitted temperature of the lamp base, dictated by the construction (200°C for E27 and BY22 due to the cement and 250°C for E40, due to the mechanical construction).

2. The maximum temperatures of the outer bulb wall are 450-650°C for the tubular lamp types and 350°C for the ovoid types.The ovoid types are mostly covered with a powder – diffusing or fluorescent – and these powders reduce in efficacy at temperatures higher than 350°C.
For lamps with no outer jacket, such as MHD-SA, the maximum values allowed are somewhat higher:
300–350°C pinch temperature and 920 –980°C bulb wall temperature.

When built correctly into a luminaire, higher ambient temperatures (which are limited by the luminaire) do not influence the behavior of HID lamps. Common values for indoor luminaires are 25°C, and for outdoor luminaires 35°C, while some industrial luminaires can have 45°C ambient temperature as maximum. The temperature inside a luminaire will increase when, due to inadequate maintenance the light cannot leave the luminaire unhindered, (e.g. dirty front glass or optics). Then there can be a slight negative influence on lifetime and light output, especially with SON and metal halide lamps.

Optimum operation

There are many different types of HID lamps, each in different lamp wattages, lamp voltages and lamp currents. Each type has its own advantages and disadvantages, to be found in the lamp data sheets.
What they have in common though, is that they need the correct ballast and ignition system for optimum performance. In fact, each type needs its own specific gear. For this reason one should take care to use the recommended gear in combination with the chosen lamp. Especially when using electromagnetic ballasts, the combination must be correct for the available mains voltage (220, 230 or 240 V / 50 or 60 Hz). HF ballasts cover a wider mains-voltage range, which can be found in the product data sheets.
When the wrong components are chosen, one can expect problems: for example, with:
- lifetime of lamps and gear
- temperatures
- starting/run-up
- stable burning
- radio interference
- light output

The burning position has also to be taken in account for correct operation.

Lamp life and depreciation

There are various different definitions of the lamp life:
- the technical, individual life is the number of hours after which one particular lamp fails.This greatly depends on the practical circumstances, and is therefore of no practical use.
- the guaranteed life is a certain agreement by contract between the supplier and the user.The operating conditions are specified in the contract.This lifetime can differ from the concepts of life normally used.
- the average rated life time is the number of burning hours which have elapsed when 50 per cent of a large batch of lamps have failed.This life-expectancy figure is normally published by the lamp manufacturers
- the economic life is the number of burning hours after which the total light output of an installation, under specific conditions, suffers a depreciation of about 30 per cent.
- the economic life, based on running costs is the number of operating hours between group replacements of lamps for which the calculated running costs are the lowest, without the lighting level dropping below a specified minimum value. The most important cause of light depreciation (declining luminous flux) is the blackening of the discharge tube by particles from the electrodes: emitter and tungsten. A certain amount of lamp blackening during life is normal and unavoidable.The blackening is caused by a thin layer of electrode material deposited during life on the inner wall of the discharge tube. However, accelerated blackening can also occur when radiation (infrared) is reflected back to the discharge tube by the optical system or when the volume of the optic is too small for a proper heat balance.A second reason for light depreciation is when a fluorescent powder is used. The powder ages due to photochemical reactions; the crystals will slowly lose their ability to transform the UV into visible light.

The data published by lamp manufacturers for life expectancy and lumen depreciation are obtained from large representative groups of lamps in laboratory tests under controlled conditions (Figs. 16 and 17).

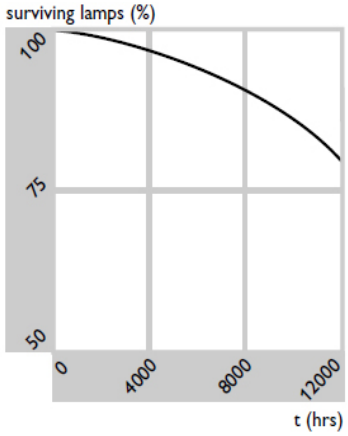


Fig. 16. Life expectancy curve of high-pressure mercury lamps when operated under standard conditions.

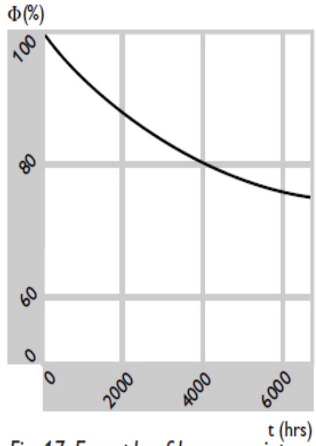


Fig. 17. Example of lumen maintenance curve of a metal halide lamp.

These tests include, amongst others:
• nominal supply voltage and appropriate circuitry,
• specified burning position,
• specified switching cycle,
• free burning, mounted on test racks (
• no vibrations or shocks,
• specified ambient temperature, mostly 25°C.
Any change in these circumstances will affect the lifetime. The major end-of-life causes and related behavior of a HID lamp are:

1.The many chemical reactions that are taking place in the discharge tube, causing the tube to leak. The hot gasses will flow through this leak into the outer bulb, noticeable as a weak discharge in the outer bulb. In very rare cases, the discharge tube will break and hot parts may cause a rupture of the outer bulb. In general, HID lamps will reach end of life passively, without shattering of the outer bulb.

2.The chemical composition changes or the operating temperature is too high: the lamp voltage rises and the lamp starts cycling and/or extinguishes.

3.The outer bulb or discharge tube leaks very slowly: the lamp changes colour and will fail to operate in a short time span.

4.An overload, such as a short-circuited ballast or, say, a 35W lamp in a 70W installation, will result a short life, with a possible shattering of the outer bulb. Until now, it was not possible to protect the lamp against such an overload situation.

5. Rectification (DC current) can occur when one electrode is worn out and the other is still emitting electrons.This will introduce DC current in the circuit with possible overheating of the ballast.A protection device in the circuit, such as a thermal switch, built in into the ballast, will protect the circuit when this happens (see IEC 61167).

6.A loose contact in the circuit or lamp can cause uncontrolled current in the circuit. Also here a thermal switch or another device will protect the system.

In the case of quartz lamps there is a risk of explosion at end of life due to the re-crystallization and weakening of quartz material at the hottest part in the burner.As a precaution against this risk, it is always recommended that a front glass be used with this type of lamp.Very few burners will shatter at the end of life because of a sudden overload (caused by a problem/short circuit in the gear). However, because shattering cannot be excluded, some types of lamps must be burnt in a fully enclosed luminaire that is able to contain all the broken (hot!) parts of the lamp.With some other types, all broken parts will be contained in the reflector or outer envelope and therefore these lamps can be used in open luminaires.

With the exception of SOX (-E) lamps, the type of circuitry has no influence on lamp life or lumen maintenance, provided, of course, that the gear is designed to the relevant standards and specifications. For the SOX (-E) lamps the circuitry chosen will have a bearing on lamp life and even more so on lumen output.

Dimming is only permissible with SON (-T) lamps. Provided that lamps are always started at nominal conditions and that dimming to less than 50 per cent of the nominal power is carried out slowly. Operating a lamp with a 220 V ballast on a 230 V mains must be seen as over-running and will reduce both lamp life as well as ballast life.

Influence of switching cycle

Nowadays HID lamps may be required to be switched on and off more than only a few times per 24 hours, especially when they are used in combination with controls, such as movement detectors or light cells. Since frequent switching generally has a negative influence on the lifetime of HID lamps, the lamp lifetimes as published by the manufacturers are usually based on tests with a specific switching frequency. For lamps, used in sports lighting installations, the cycle on which the figures are based are, for instance, 5 hours on and 1 hour off, whereas for other outdoor applications and indoor use a sequence of 11 hours on and 1 hour off is mostly used. Especially when the switching frequency is so high that the lamp has to restart while it is still warm, problems are particularly to arise.The control gear will repeatedly try to re-ignite the lamp.This will continue until the vapour pressure is sufficiently low for the lamp to restart. The ‘average’ lamp-life data presented are typical values. They are the average of different tests. Batch deviations occur due to deviations in the materials used and in lamp processing, and to different types and batches of gear. Differences in ‘application parameters’, such as mains voltage, ambient temperature and starter, can also have a negative influence on lamp life. The standard deviation of the ‘typical’ lamp life values is 10 to 20 per cent.

Stroboscopic effect, flicker and striations

The stroboscopic effect is the apparent change of motion of an object when illuminated by periodically varying light of the appropriate frequency. There are various sorts of flicker.The light output of a lamp varies with the level of the mains supply voltage. Therefor there are restrictions set in IEC 61000-3-3 for voltage fluctuations as caused, for example, by a varying electrical load, (see Fig.18). The disturbing effect depends not only on the magnitude of the voltage fluctuations, but also on the repetition rate.

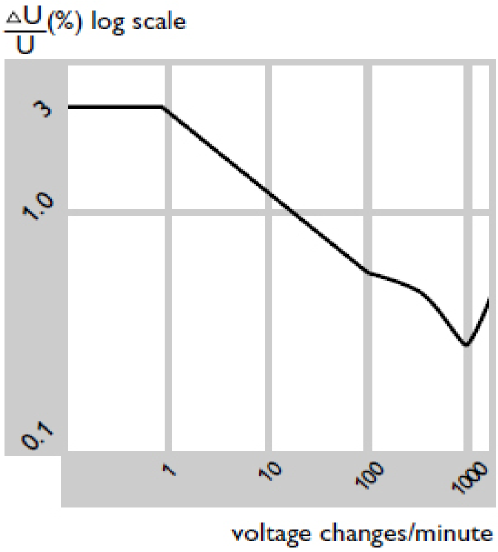


Fig. 18. Magnitude of maximum permissible voltage changes with respect to number of voltage changes per minute.

The most dangerous frequency is between 2.5 and 15 periods per second. Car drivers can experience this when driving along a tree-lined road when the sun is low at the horizon. It can also happen in a tunnel when the luminaires are badly spaced in relation to the speed of the traffic. An asymmetric lamp voltage results in a light flicker with the mains frequency (50/60Hz). In normal situations the lamp voltage is symmetrical.This kind of flicker can occur at the end of the life of a lamp, when an ignitor abusively comes in every positive or negative period or when the electronic ballast has a defect. Lamps burning in vertical position are more sensitive than horizontal burning lamps Another sort of flicker is that caused by the fluctuation of the light output of the lamp on account of movement of the discharge arc on the electrodes.Although the length of the arc remains constant, the place where it strikes the electrode may vary.This 'dancing' of the arc has no constant frequency and depends on various factors, including lamp position, supply voltage, temperature, age of the lamp (electrode). This phenomenon is also called flatter and has an irregular low frequency (< 50 Hz). Striations are noticeable as a pattern of more or less bright regions in the (elongated) discharge tube and only occur in low-pressure lamps (TL and SOX).

This pattern can move along the discharge tube. It may appear when the lamp is cold or when the lamp is dimmed down too much. An HID lamp operating on an alternating current will exhibit a fluctuating light output, as the lamp extinguishes and restrikes every half cycle of the supply.The lamp current goes through zero twice per period and the light output varies to some extent with these cyclic changes in the lamp current. So this light alternation (light ripple) has double the mains frequency and may cause the stroboscopic effect, (see as example Fig. 19).

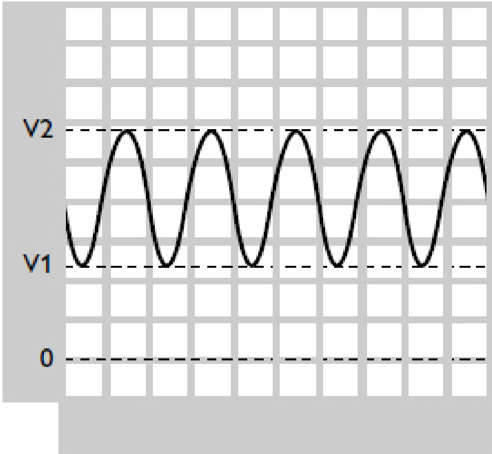


Fig. 19. Light output of 2000 W lamp.

The effect is different for mercury/metal halide and high-pressure sodium lamps.
Here the fluctuation of the light output is noticeable and may cause a stroboscopic effect, created by the pulsating light.The solution is to spread the lamps over the three phases of the supply (see Fig. 20), so that the minimum light output of one lamp coincides with high light outputs of the two other lamps.

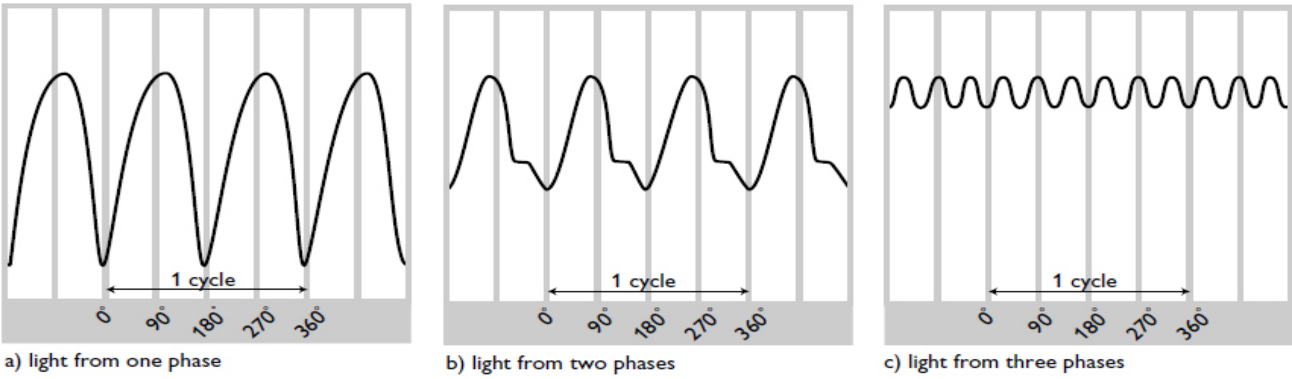


Fig. 20. Prevention of the stroboscopic effect by spreading the lighting over the three phases of the supply.

Low-power lamps are more sensitive to flicker than lamps with higher power.This is one of the reasons why dimming of these lamps is not recommended on conventional gear . With the fully electronic HID-ballasts for low-wattage metal halide lamps there is no flicker at all. Mercury lamps with the fluorescent layer on the outer bulb also contain some phosphorescent substance with after-glow properties, thus eliminating the light ripple to a large extent.

Sodium lamps

Here the fluctuation of the light output is scarcely noticeable.This is because the sodium discharge exhibits a certain degree of after-glow, which is normally sufficient to bridge the dark periods in the 50/60 Hz cycle of the mains voltage. Although these lamps are less sensitive to flicker than the previous group, some stroboscopic effect may sometimes occur, as, for example, with aged lamps.

HID lamps and cameras

Light fluctuations in HID lamps may also have an effect on the quality of camera pictures.
This phenomenon may become apparent when CCD colour cameras operate in auto-shutter mode and the lighting of the area is predominantly with HID lamps. The auto-shutter mode is normally selected when the cameras are equipped with manual or fixed iris lenses and the automatic light response is controlled by an electronic shutter system in the camera.The greater the amount of light, the shorter the shutter time, and hence the shorter the period of light integration in the sensor. For example, with a shutter time of 1/1000th of a second, the light integration of the CCD sensor is only 1 ms.Within the normal CCIR scanning period of 20 ms (50 Hz) the 1/1000th of a second the light integration time is just a snap-shot in the normal frame scanning period. Hence, the sensitivity of the camera is reduced. As described before, the light output of HID lamps varies continuously from minimum (at zero crossing) to maximum during the positive and negative phases of the mains voltage, twice during one mains voltage cycle. In other words: the HID lamp is flashing 100 times per second. Due to the inertia of our eyes, viewing a scene illuminated with HID lamps, gives the impression of a white and continuous light output.

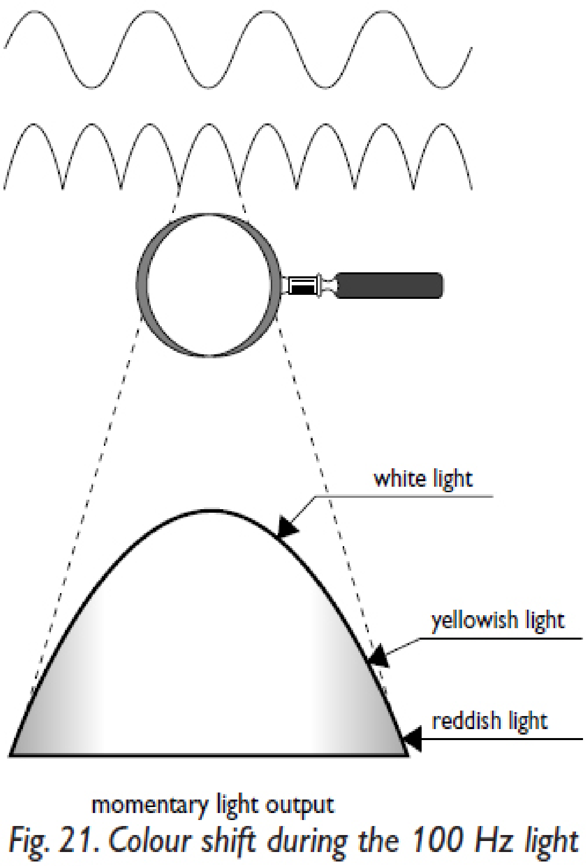


Fig. 21. Colour shift during the 100 Hz light ripple of a HID lamp.

The light ripple of a HID lamp is illustrated in Fig. 21. When the automatic shutter in the camera is switched off, the two light ripples of the lamp are integrated during the normal 20 ms frame integration time of the sensor and consequently the light impression is white.This is illustrated in Fig. 22.

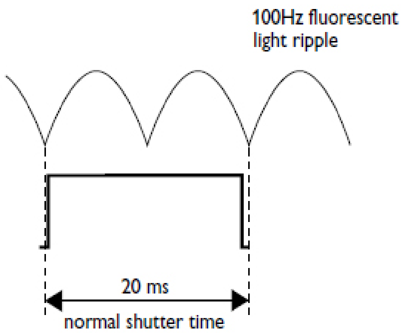


Fig. 22.The 20 msec frame integration time of a CCD colour camera with the automatic shutter switched off, compared with the 100 Hz light ripple.

Using the automatic shutter in sufficiently illuminated scenes, the shutter speed increases. Consequently, light integration in the sensor takes place during a shorter period of time. Depending on the position where the light integration (snap-shot) takes place with respect to the mains phase (light ripple), it is now possible that a TV frame is shot during the non-standard excitation of the light, (see Fig. 23).

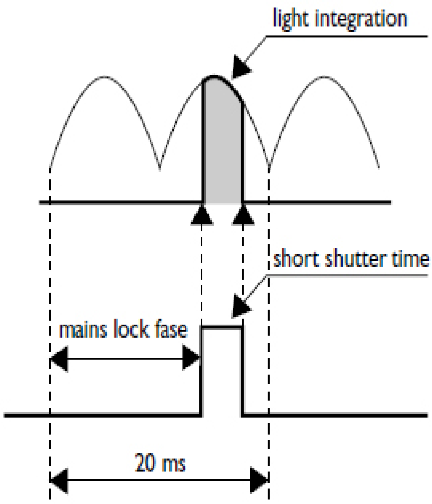


Fig. 23. Using the automatic shutter and with the camera locked to mains frequency, it is possible to shoot stable and white pictures.

It can be said that the light at this point in time is not white and that the light output is less. If the phase of the camera shutter remains constant with respect to the mains phase, the automatic light control and the white balance circuits in the camera will compensate for these effects and stable pictures are produced.This situation is obtained by locking the camera frame synchronisation to the mains (mains lock). When there is no fixed phase relationship between the scanning frequency of the camera (free running) and the mains frequency, the camera will take a snap-shot of the scene at varying phases of the lamp light output. This causes a colour fading to become visible. The extent of colour fading depends on the type of light in the area. In applications where the scene is illuminated with just one lamp, stabilised by conventional gear, the risk of colour fading is at its maximum.

It is recommended that cameras be locked to the mains frequency and that the phase of the camera synchronisation be adjusted such that the camera signal output is maximum. If mains lock is not possible in such an application, the lens iris should be closed to the point where the colour fading just disappears. Now the shutter speed is less (full frame integration) and there is the additional benefit that the sensor smear effect is less.

This method cannot be used in applications that need short shutter speeds to suppress movement blur. In other cases (three-phase installation or high-frequency stabilised) this phenomenon will not occur.

Dimming
SODIUM LAMPS

For Sodium lamps , dimming to 50% lamp power (flux at 35%) has no influence on lamp life or lumen maintenance, and there are no pronounced colour point changes. Below 50% lamp power the colour will shift and the output approaches a monochromatic colour. Recent experience with the modern electronic ballast's family shows that dimming to 35% lamp power (20% flux) has no significant effect on lifetime and maintenance.

Other HID lamp types

The other HID lamp types do not offer benefits with regards to dimming. On the contrary, mostly exhibit a dramatic shortening in lifetime, sometimes with extreme colour shifts.

Shocks and Vibrations

The length of the discharge arc, together with the vapour pressure in the discharge tube, determines the lamp voltage. If the balance of the discharge arc is disturbed by shocks or vibrations, the arc will nevertheless try to maintain itself. But to do that, it has to travel a longer path than when it is an undisturbed line, and therefore it requires a higher voltage. If that higher voltage is not available, the lamp will extinguish. After some time the lamp will start automatically. But until that happens, the electrodes will have had to withstand the high ignition voltage and current, which are reducing the lamp's life. Due to their greater arc length, low-pressure sodium lamps are more sensitive to vibrations than other HID lamps. In general, HID lamps have a superior resistance to shocks and vibrations compared to incandescent and halogen lamps.

Burning position

Some lamp types, such as Mercury and Sodium , can operate in any position. Others are subject to certain restrictions, as can be found in the product information of the HID lamps.These restrictions ensure proper functioning of the lamps and/or influence the lamp life (positively). Metal halide lamps in general are to be operated horizontally, unless specifically designed for vertical burning, as in the case with Metal Halide marked (BU = base up). CDM-T and TC have universal burning position.
When metal halide lamps are used in positions other than specified, the different metals in the gas mixture will start to separate.They 'float' on top of each other, which causes layers of different coloured light: a rainbow effect. In that case, the lamp colour normally shifts. Low-pressure sodium lamps are also best operated horizontally.The lower wattage lamps may be used vertically, but the base should then be at the top.This is to prevent a cool area being created behind the electrodes which would affect lamp life in two different ways: the sodium, which would collect there, would attack the electrodes and the even distribution of the sodium over the discharge tube would be disturbed.

The lamp voltage of a horizontal operating lamp is somewhat higher than when vertical operated. Due toconvection the discharge arc is curved upwards, giving a longer length.Therefore a horizontal lamp will extinguish earlier in lifetime than vertical operated.

Colour rendering and colour shift

The colour properties of HID lamps can be characterised by the following parameters:

- chromatic co-ordinates (colour points X,Y),
- correlated colour temperature (Tk),
- general colour rendering index (Ra).

The colour properties of HID lamps depend mainly on the gases used and the temperature of the discharge tube. The low-pressure sodium lamp mainly emits radiation with a wavelength of about 589 nm -a radiation perceived by us as orange-yellow.This radiation is characteristic for low-pressure sodium.

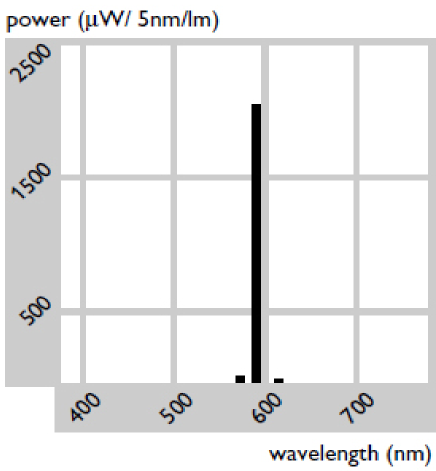


Fig. 24. Spectrum of a SOX lamp.

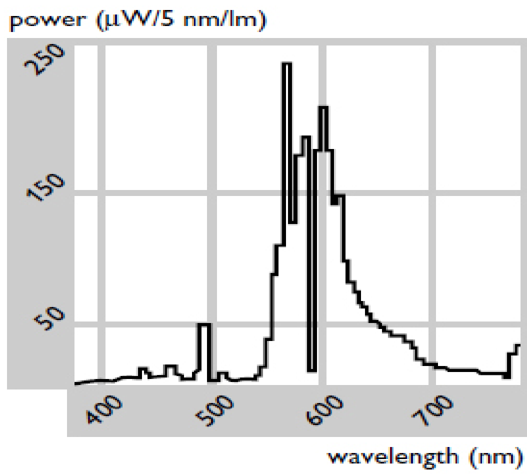


Fig. 25. Spectrum of a SON-T lamp.

When the pressure in the sodium discharge is increased, the monochromatic spectrum changes into a "multi-line" one, and the typical low-pressure sodium colour changes into golden-white light.
The radiation of mercury vapour lamps is distributed over the spectrum, in the UV, violet, blue, green and yellow ranges, so that the light of the mercury discharge makes a whiter impression than that of the sodium discharge. The more wavelengths there are in the visible part of the spectrum of a gas discharge and the more they are distributed over the spectrum, the more natural the light of that lamp appears to us. For that reason use is also made of mixtures of a number of metals. An example of this is the HPI-lamp.

The chromatic co-ordinates X,Y and Z represent the amount of red, blue and green in the light.
As X+Y+Z = 1, only X and Y are published. The correlated colour temperature defines the appearance of the white light and is expressed in Kelvin. Low colour temperatures (< 3300K) give a warm impression (yellowish), while a high colour temperature (>5000K) gives a cool impression (blue).
With these two figures we can place any lamp in the Colour Triangle, (see Fig. 27):

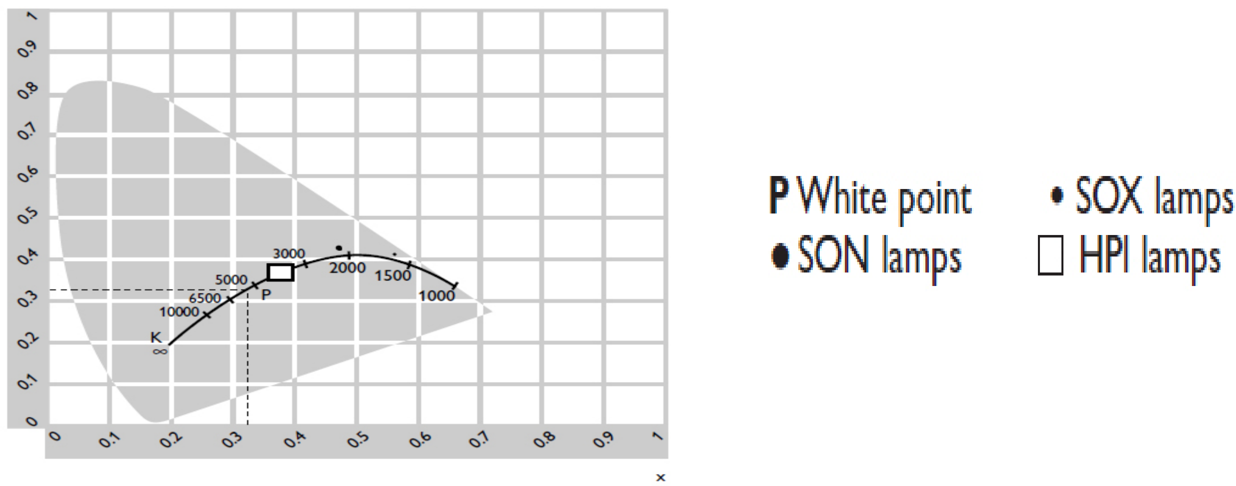


Fig. 27. CIE Chromaticity Diagram (Colour Triangle).

• SOX low-pressure sodium lamps: correlated colour temperature of about 1700K,
• SON (- T) high-pressure sodium lamps: correlated colour temperature of about 2000K,
HPL-N high-pressure mercury lamps and HPI(- T) metal halide lamps: correlated colour temperature between 3200 K and 4700 K.

The Colour Rendering Index (Ra) gives an indication of how colours appear under a given light source. The colour-rendering index of most HID lamps is fairy low. In the case of the SOX low-pressure sodium lamp there is absolutely no question of colour rendering.

The SON (-T) high-pressure sodium lamps have a Ra of 20 to 60.

The newest lamps, such as MHN(W)-TD and CDM lamps, have colour rendering indices that make them suitable for applications in which proper colour rendering is required. HID lamps with poor colour rendering will have to be used in applications where colour is of secondary importance and where these lamps are preferred on account of other positive properties. Changes in the discharge tube temperature cause shifts in the composition of the metal vapour mixture, which then result in colour point and consequently colour temperature shifts.

The usual manufacturing tolerances already give a certain spread in the chromatic co-ordinates, especially with metal halide lamps.As lamp life progresses, the discharge temperature will rise, e.g. owing to blackening, so that the colour temperature will become lower. External factors such as the mains voltage, the ambient temperature, the spread in ballast impedance or the burning position (metal halide lamps) can have some effect. Conventional control gear cannot correct for these phenomena. But by monitoring the actual mains voltage, lamp voltage and lamp current, electronic ballasts can regulate and supply the lamp with, for example, a constant lamp power. Or a constant colour temperature can be realised (e.g.White SON). Or a certain lamp can have two different colour temperatures, when supplied with two different lamp currents.

Photochemical reaction (PET, D.F.)

Within the spectrum of electromagnetic waves that are produced by a discharge we can distinguish three groups of radiation: Infrared, visible and ultraviolet (UV). Sometimes the lamp is so designed that it passes a part of the UV radiation:

- on purpose for lamps where the UV is used for photochemical processes: e.g. some of the reproduction techniques are based on it, as is suntanning of the skin, and dermatological treatments of the skin

- unintentionally, in which case special filters must be used to protect against this kind of radiation.
This unintentional output of UV is of importance in areas where people work, where materials are used that are sensitive to UV, or both. In order to quantify the impact of UV, two factors are introduced:

- PET: Permissible Exposure Time at an illuminance level of 1000 lux, i.e. the time that an average person can be exposed to 1000 lux without any harmful or negative consequence. If this factor is 24 (hours) or more, no damage is to be expected

- D, D.F. or fc: Damage Factor, expressing the damage that is done to exposed objects, e.g. fading of textiles. Both figures can be found in the lamp specifications.

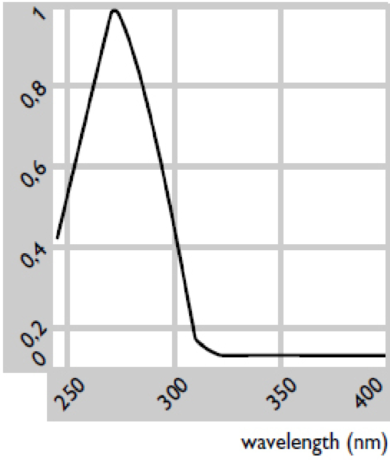


Fig. 28. Relative spectral effectiveness versus wavelength.

The time needed to acquire this maximum dose can be calculated from the spectral power distribution of the light source and an assumed illuminance level of 1000 lux. This time is called Permissible Exposure Time (PET). It is clear that the time humans are exposed to the light should not exceed the PET. From the so-called NIOSH-curve, see fig 28, it can be seen that the relative effectiveness of UV depends on the wavelength.The effectiveness is especially high for short wavelengths, viz. 250-320 nm. Another effect of UV (and blue light) is the risk of fading (= losing colours) of the goods illuminated by it.

This fading risk depends on:

• the type of material that is being illuminated. Studies show that some materials are extremely sensitive to UV radiation.
• the illumination level, defined by the lighting design: very high beam intensities look theatrical, but also involve very high fading risks.
• the exposure time until fading becomes visible.
• the damaging effect of the UV emitted by a light source.

The damaging effect of the source can be expressed by a damage factor (D/fc). It must be noted that not only UV causes fading, but also the radiation in the visible part of the spectrum, where blue is most damaging and red has a low damaging effect.

The relation between these variables is:

Fading risk = E*t*D/fc
in which:

E = illuminance value on the objects
t = exposure time
D/fc = damage factor of the light source

The UV radiation emitted by the discharge tube can be filtered by the outer bulb, by a fluorescent layer on the outer bulb, by the UV blocking front glass of a luminaire or by special UV filters.
When the radiation is not properly shielded, or when exposure times are exceeded, harmful effects can occur to people: conjunctivitis ('welding eyes' or heavy irritation of the eyes), skin irritation etc.

HID Electromagnetic lamp control gear

The term 'ballasts' is generally reserved for current limiting devices, including resistors, choke coils and (autoleak) transformers. Other items of auxiliary equipment are compensating capacitors, filter coils and starters or ignitors. Some systems (SOX) use an additional series capacitor for stabilisation. With all these components all the control functions that are necessary for the operation of standard HID lamps can be carried out.

Stabilisation

Stabilisation, the need for current stabilisation for HID lamps has been described, resulting in the following two formulae:

$$I_{lamp} = (\overrightarrow{V_{mains}} - \overrightarrow{V_{lamp}}) : Z_{ballast}$$

and:

$$P_{lamp} = V_{lamp} \cdot I_{lamp} \cdot \alpha_{lamp}$$

where

I_{lamp} = the current through the lamp
V_{mains} = the mains voltage
V_{lamp} = the voltage across the lamp
$Z_{ballast}$ = the impedance of the ballast
P_{lamp} = the power of the lamp
α_{lamp} = a constant called the lamp factor

From these formulae it can be concluded that the power of the lamp (and therefore the light output) is influenced by:

- the lamp voltage V_{lamp}, which in turn is highly dependent on the operating temperature , Ambient and operating temperatures) and on the lamp current, according to the negative lamp characteristic.

- the lamp current I_{lamp}, which is dependent on the mains voltage ,Effects of mains voltage fluctuations), the lamp voltage and the linearity of the ballast impedance. Stabilisation of the lamp power, or rather: suppression of its possible variations, is therefore of the utmost importance

Perfect suppression, however, is impossible with the standard EM ballasts, and it is important to know the margins within which the lamp power varies – for example, when calculating the maximum power capacity needed for an installation.

There are two tools for indicating the influences of the factors mentioned: the ballast and lamp lines, and the socalled trapezoidal or quadrilateral diagram.

Ballast and lamp lines

A set of ballast and lamp lines is shown in Fig. 29.The ballast lines indicate the relationship between the lamp voltage and the lamp power for a given ballast (viz. a given ballast impedance) and for three levels of mains voltage: the rated level of the ballast, 95 per cent of the rated level, and the rated level plus 10 V.There is a set of such lines for each type of ballast, available at the ballast manufacturer.The figure gives the lines for a typical choke coil ballast. Four so-called lamp lines are also plotted in the diagram (dotted lines).A lamp line gives lamp voltages and lamp powers for different levels of mains voltage. For example, the first lamp line gives lamp voltages and lamp powers at the 100-hour condition of the lamp (L_{nom}).

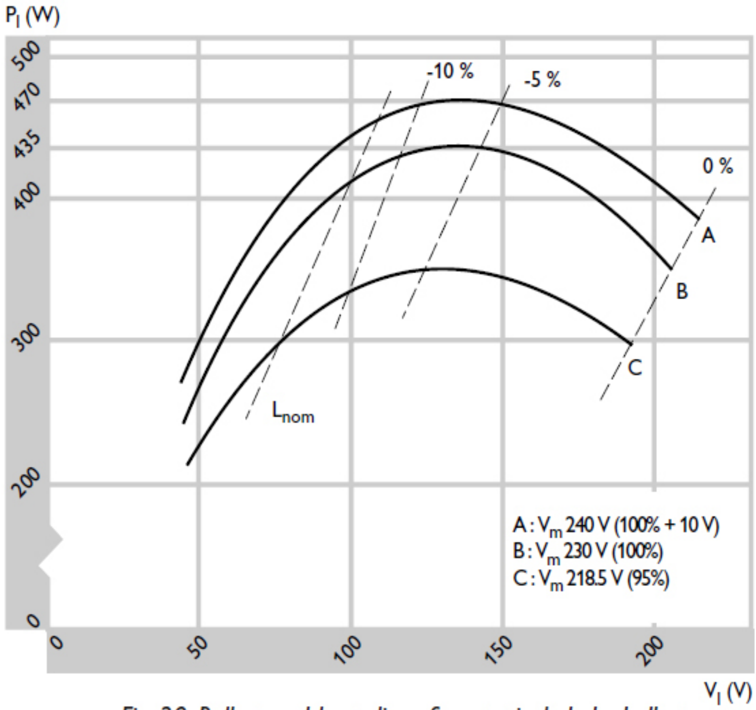


Fig. 29. Ballast and lamp lines for a typical choke ballast, based on 230 V mains voltage.

The line marked 0% gives lamp voltages and lamp powers above which lamp operation is not possible. It is called the extinction line: it indicates the set of extinguishing lamp voltages (at which the lamp starts cycling) at different levels of the mains voltage, provided that these are steady.
If, on the other hand, the mains voltage is not steady, and should suddenly drop by 5% or 10%, the extinguishing voltage will drop with it.The lines marked -5% and -10% give the extinction voltage for these situations. The operation point of a HID lamp lies at the point of intersection of the relevant ballast line and lamp line. Since the lamp voltage of high-pressure sodium lamps increases during life, the actual lamp line will shift to the right of the initial one

For a given electrical circuit (ballast + mains voltage), this means that the operating point will travel along the ballast line during lamp life.According to the rate of increase of the voltage, the lamp power will first rise and after some time fall again.

Quadrilateral diagram

The limits within which the operation point must stay for satisfactory lamp performance can be conveniently specified by means of a so-called quadrilateral (or trapezoidal) diagram, especially for SON lamps, (see Fig. 30).

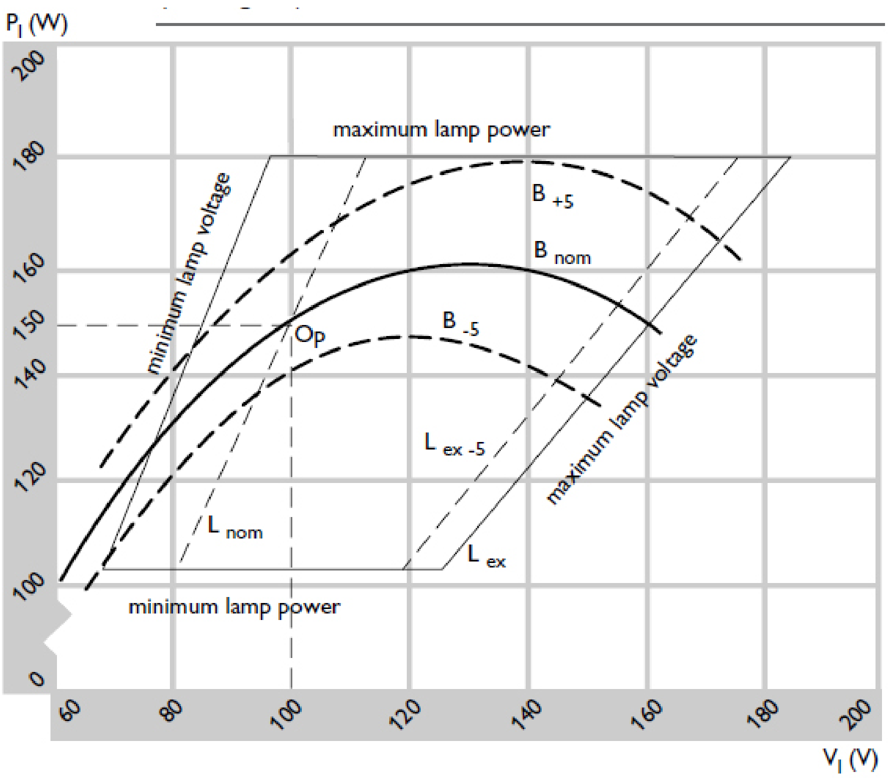


Fig. 30. Quadrilateral diagram of 150 W high-pressure sodium lamp.

B_{nom} = ballast line for nominal mains voltage
B_{+5} = ballast line for 5% over-voltage
B_{-5} = ballast line for 5% under-voltage
L_{nom} = lamp line for nominal operating conditions
L_{ex} = lamp line for maximum lamp voltage (extinguishing line)
L_{ex-5} = extinguishing line for 5% under-voltage
O_p = operating point

The upper boundary defines the maximum permissible power dissipated in the lamp, for which its lifetime is still acceptable.The lower boundary, marking the minimum permissible power in the lamp, is to ensure an acceptable luminous flux and a satisfactory warming-up time. The left-hand boundary defines the lowest permissible lamp voltage, and its position is marked by a lamp line.
This line is not very critical, but remaining within this boundary can indirectly prevent an excessive lamp current.The right-hand boundary is also marked by a lamp line and indicates the highest permissible lamp voltage, above which the lamp will extinguish. In view of the possible occurrence of mains voltage surges, the lamp should always be operated well within this boundary line. In order to avoid undesirable variations in light output as a consequence of mains-voltage fluctuations, the lamp voltage must be not more than approximately half the value of the mains voltage (100 to 130 V), and the impedance should be as linear as possible.

Responsibility of ballast and luminaire manufacturers

Two of the main factors influencing lamp performance have been dealt with: the ballast properties and the operating temperature. Obviously, the first factor is of concern to the ballast manufacturer, whilst the second is chiefly determined by the design and construction of the luminaire.
Thus, together with the lamp manufacturer, the ballast and luminaire manufacturers impose certain limitations on their products so as to ensure that they operate within specification. When selecting the lamp circuit and determining the design of a ballast, the ballast designer will make sure that variations in the supply voltage - caused by ballast tolerances and mains voltage fluctuations - will under no circumstances cause the ballast line to cross the lower or upper boundaries of the quadrilateral diagram. The lamp designer, meanwhile, has to keep the initial value of the lamp voltage to the right of the left-hand boundary line, by taking care that the tolerances on lamp voltage are as tight as possible. He must also ensure that the lamp voltage does not cross the right-hand boundary line before the lamp has reached its predicted life span. Similarly, it is the responsibility of the luminaire manufacturer to ensure that the discharge tube cannot reach so high a temperature that the operation point exceeds, or even lies near to, the right-hand boundary line of the quadrilateral diagram.

Ignition and re-ignition
Ignition

Earlier section Lamps, Ignition, the need for ignition of an HID lamp has been described.
Basically, there are four different ignition systems

1. no external ignitor,
2. two-pole parallel ignitor,
3. three-pole semi-parallel or impulser ignitor,
4. three-pole superimposed pulse or series ignitor.

The role of the ballast in the ignition process depends on the ignition system:

ad 1: a) The lamp can ignite on the available open voltage:
I) The mains voltage is high enough, as with Mercury lamps. The ballast has no special ignition function.
II) The mains voltage is not high enough. The ballast must produce the required open-circuit voltage, as with the autoleak transformers for SOX lamps.

b) The lamp cannot ignite on the available opencircuit voltage: An internal starting device must produce the necessary peak voltage, as with the glowswitch starter in SON(-I).The peak voltage L dI/dt depends on the ballast impedance, so ballast and starter must be specific to the lamp type.

ad 2: The ballast impedance determines the current for charging the ignitor capacitor and so the ignition peak. Ballast and parallel ignitor are therefore a fixed combination for a certain lamp type (SOX, HPI-T).

ad 3: With the three-pole semi-parallel ignitor system the ballast also reacts as a voltage transformer to transform the ignitor capacitor voltage up to the required peak voltage. The location of the tapping on the ballast is therefore very critical, as it is situated in such a way that one semi-parallel ignitor can be used for several lamp types (SON) with the appropriate ballasts.

ad 4: In the three-pole superimposed pulse or series ignitor system, the ballast has no special function during ignition. In all cases the ballast has to limit the current through the lamp to the specified value during ignition and run-up of the lamp. Except in case 4, the ignition peak voltage is present on the ballast terminal that is connected to the lamp.

Re-ignition

Energy is supplied to the discharge in the form of electrons.The lamp current, just like the mains voltage, is sinusoidal, with a frequency of 50 Hz or 60 Hz. If the energy flow is zero (at lamp current reversal), the lamp stops burning and in theory would have to be re-ignited. This could be done by supplying additional energy to the electrodes via a higher lamp voltage, as is done when initially starting the lamp. But from the moment the lamp has reached its stationary condition, the lamp voltage is constant. And yet, in practice, the lamp does not extinguish at current reversal.The reason for this is that the phase shift introduced by the inductive element of the ballast ensures that the mains voltage is not zero at the moment that the lamp current is zero. Because of the inductive properties of choke coil ballasts, a phase shift occurs between the mains voltage and the lamp current (see Fig. 31). So, at the moment of current reversal, the lamp voltage would be equal to the mains voltage, since the voltage over the ballast is zero.The difference (gap) between the mains voltage and the momentary lamp voltage as a consequence of the phase shift ensures proper re-ignition of the lamp at the moment the current passes the point of reversal (zero-point A in Fig. 31).

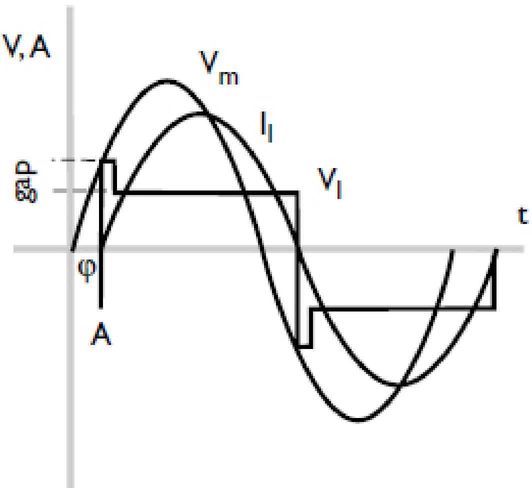


Fig. 31. Lamp current (I_l), lamp voltage (V_l) and mains voltage (V_m) as functions of time.

If now the lamp voltage rises during its lifetime, the gap between the mains voltage and the average lamp voltage decreases. In the end it will become too small to ensure re-ignition (see Fig. 32), and the lamp extinguishes. It has to cool down before it can start again. After restarting, the lamp voltage quickly rises to the extinguishing level again.The lamp starts cycling and has to be replaced. By using self-stopping ignitors this cycling process can be interrupted.

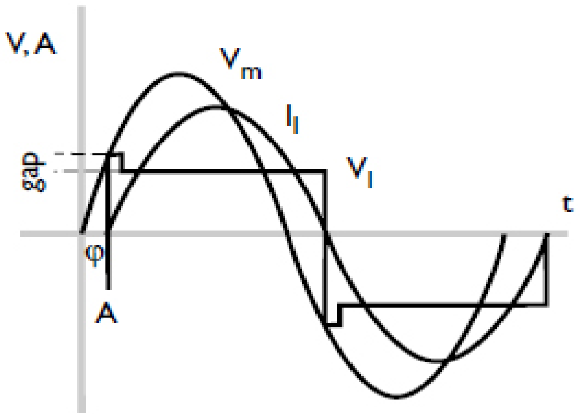


Fig. 32. Voltage gap between Vm and Vl being too small to re-ignite the lamp.

Types of ballasts

1 Resistor ballasts

Current limitation by means of resistor ballasts is a very uneconomic form of current limitation.This is because electrical energy is dissipated in the form of heat in the resistor. Limitation of lamp current by means of a simple resistor is only used in self-ballasted blended-light lamps , where a filament is connected in series with the discharge tube.This filament, incorporated in the lamp, also takes part in the light production of the lamp. For this reason, the luminous efficacy of blended-light lamps is lower than that of other HID lamps. On the other hand, the advantage of this system without external ballast is that an installation with incandescent lamps can easily be converted to a system with a much longer life by simply replacing the incandescent lamps by blended-light lamps.An extra advantage of such an exchange is the higher efficay of blended-light lamps compared to the equivalent incandescent versions.

2 Capacitor ballasts

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

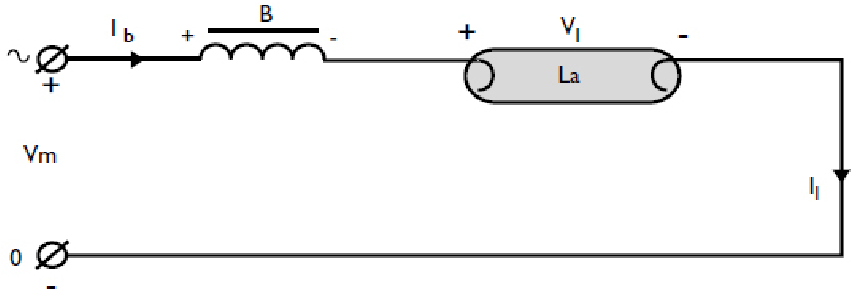


Fig. 33. Schematic diagram of a HID lamp operated on a choke ballast.

3 Chokes, inductive or reactor (R) ballasts

Choke coils are frequently used as current limiting devices in gas-discharge lamp circuits (see Fig. 33). They cause somewhat higher losses than does a capacitor, but produce far less distortion in the lamp current at 50 Hz. Moreover, in combination with an ignitor, they can be made to produce the high voltage pulse needed to ignite the lamp. In practice, a choke ballast consists of a large number of windings of copper wire on a laminated iron core. Current limitation by means of resistor ballasts is a very uneconomic form of current limitation.This is because electrical energy is dissipated in the form of heat in the resistor. It operates on the self-inductance principle.The impedance of such a ballast must be chosen to suit the mains supply voltage and frequency, the lamp type and the voltage of the lamp, to ensure that the lamp current is at the correct value. In other words, for each supply voltage, each type of lamp requires its own choke as a ballast with a specific impedance setting.
Heat losses, occurring due to the ohmic resistance of the windings and hysteresis in the core, much depend on the mechanical construction of the ballast and the diameter and length of the copper wire. The right ballast for a given lamp and supply voltage should be chosen by consulting documentation and/or ballast markings. Ballasts can have taps for different lamp types (e.g. for HP 50/80 W or SON 50/70 W) or for different supply voltages (e.g. 230/240 V or 380/400/415 V). In some cases several ballasts can be combined to form a new ballast (e.g. two parallel HP 1000 W, 220 V ballasts form one HP 2000 W, 220 V ballast). But the ballast for a 400 W HP lamp is not the same as that for a 400 W SON lamp. Some ballasts may have another tapping for the connection of a semi-parallel ignitor. It is important to use the correct ignitor/ballast combination and to connect these items according to the wiring diagram on the ignitor. The most important value for stabilisation is the ballast impedance. It is expressed as the voltage-current ratio in ohms (Ω) and is defined for a certain mains voltage, mains frequency and calibration current (normally the nominal lamp current). Chokes can be used for virtually all discharge lamps, provided that one condition is fulfilled: the mains voltage should be about twice the arc voltage of the lamp. If the mains voltage is too low, another type of circuit should be used, such as the autoleak or constant-wattage circuits.
The advantages of a choke coil are:

- the wattage losses are low in comparison to those of a resistor,
- it is a simple circuit: the ballast is connected in series with the lamp. The disadvantages of a choke coil are:
- the current in a lamp with choke circuit exhibits a phase shift with respect to the applied voltage, the current lagging behind the voltage, resulting in a power factor of ca. 0.5 inductive
- a high starting current: in inductive circuits the starting current is about 1.5 times the rated current.
- sensitivity to mains voltage fluctuations: variations in the mains voltage cause variations in the current through the lamp.

4 Autoleak transformers or high-reactance autotransformers (HX)

If the mains voltage is lower than about twice the arc voltage of the lamp - as is the case with low-pressure sodium lamps - the mains voltage has first to be stepped up.This could of course be done by a separate step-up transformer.A better solution is to combine thefunctions of transformer and choke in one piece of equipment.Autoleak transformers perform this combined operation: part of their secondary winding acting as a choke coil (Fig. 34).This configuration saves on windings and thus on wattage losses, space and weight. It also improves the re-ignition of the lamp, thanks to the higher open circuit voltage.

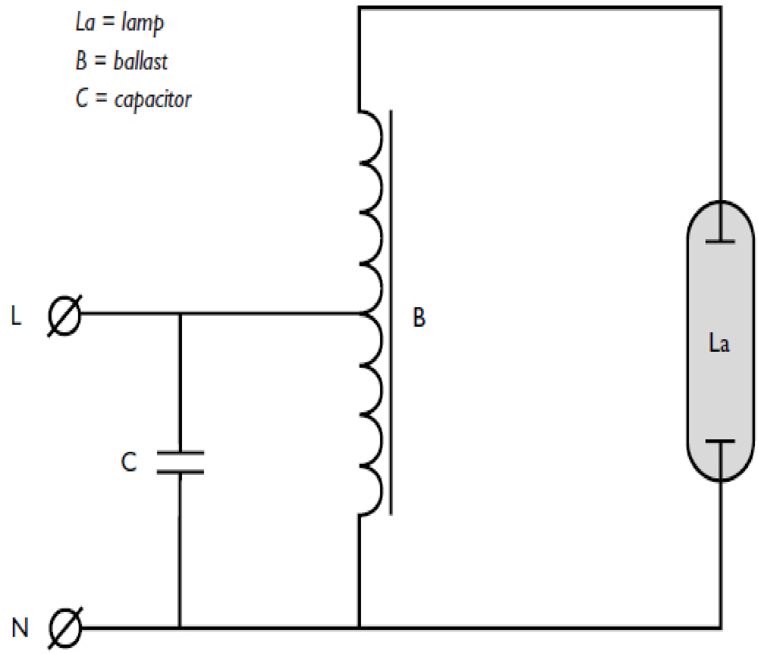


Fig. 34. Circuit diagram of a low-pressure sodium lamp with an autoleak transformer.

Just as with the choke coil, compensation capacitors may be necessary in order to improve the power factor. Autoleak transformers for low-pressure sodium lamps also fulfil the function of an ignition device, making a separate ignitor superfluous. Compared with normal choke ballasts, the autoleak transformer has the advantage of a higher open-circuit voltage (no ignitor).The disadvantages are: higher wattage losses, because such ballasts are larger and more expensive.

5 Constant-wattage hybrid circuits (SOX)

The constant-wattage hybrid circuit is shown in Fig. 35. The primary circuit consists of a linear self-inductance Z1 in series with a saturated inductance Z2.The voltage across Z2 is transformed up to the required voltage. The secondary circuit consists of a capacitor in series with the lamp.The capacitor value is well-defined with a narrow tolerance (± 4%) for stabilisation of the lamp current.

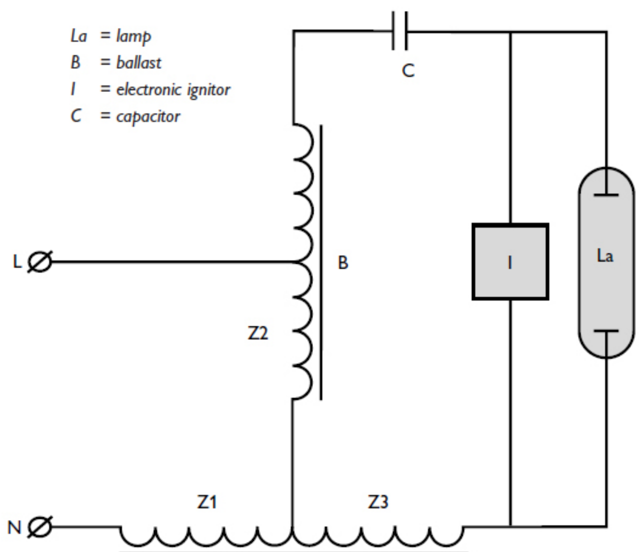


Fig. 35. Constant-wattage hybrid circuit.

Z3 is necessary to avoid flickering of the lamp, especially during run-up. An electronic ignitor with built-in capacitor is placed in parallel to the lamp and provides the voltage peaks required to ignite the discharge. It also essential for the quick re-ignition of the lamp.

The advantages of the constant-wattage hybrid circuit are:

- the system supplies a squarer lamp-current waveform, so that the dark period in each cycle is reduced, resulting in smooth re-ignition,
- mains-voltage fluctuations have little influence on the lamp wattage, because the circuit is of the constantwattage type,
- re-ignition of the lamp when warm is no problem, thanks to the electronic ignitor,
- suppression of audio-frequency signals is done by the coil-capacitor combination, so no extra filter coil is needed,
- little mains current distortion occurs, because harmonics from the lamp are attenuated in the ballast circuit,
- a good power factor. The constant-wattage hybrid circuit has no real disadvantages, although it is more complicated and physically larger than a normal choke.

6 Constant-wattage circuit

In the USA, the constant-wattage circuit is widely used in lighting systems with mercury and high-pressure sodium lamps, (see Fig. 36). It consists of an autoleak transformer with a capacitor in series with the lamp. Use of the capacitor allows the lamp to operate with better wattage stability when the supply voltage fluctuates. It performs a double function here: it takes part in the ballasting of the lamp circuit and it corrects the power factor.

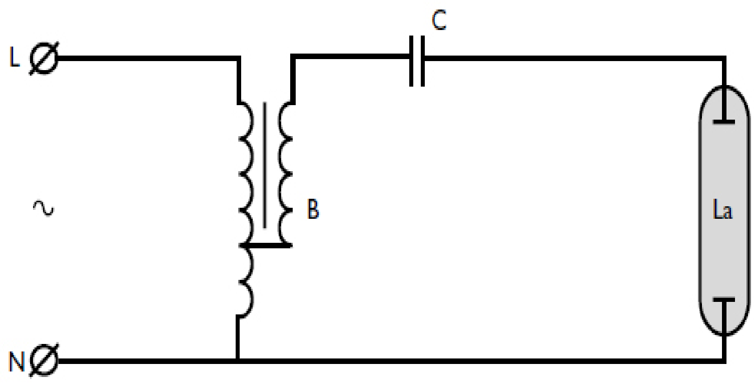


Fig. 36. Constant wattage autotransformer circuit.

The advantages of the constant wattage circuit are:

• variations in the mains voltage up to some 10 per cent have virtually no effect on the lamp current.
• a favourable power factor.
• a low run-up current. The system does, however, also have its disadvantages:
• the wattage losses in the transformer are high.
• the autoleak transformer is large, heavy and expensive.
• arc-voltage fluctuations result in considerable wattage fluctuations: the changes have to be "dissipated" by the ballast.

Maximum coil temperature tw (lifetime) and ΔT

A ballast, like most electrical components, generates heat due to its ohmic resistance and magnetic losses. Each component has a maximum temperature that may not be exceeded. For ballasts it is the temperature of the choke coil during operation that is important. The maximum permissible coil temperature tw is marked on the ballast. Coil insulating material, in combination with lacquer, encapsulation material, etc., is so chosen that below that temperature the life specified for the ballast is achieved.A tw value of 130°C is usual nowadays with a coil insulating class F (150°C) or class H (180°C). Under standard conditions, an average ballast life of ten years may be expected in the case of continuous operation at a coil temperature of tw °C.As a rule of thumb, a 10°C temperature rise above the tw value will halve its expected life (see Fig. 37). If, for instance, the operating temperature is 20°C above the tw value, one may expect a ballast life of 2.5 years of continuous operation. If no tw value is marked on the ballast, a maximum of 105°C is assumed for the coil temperature. As the ballast normally does not function continuously, the actual life of the ballast can be very long.

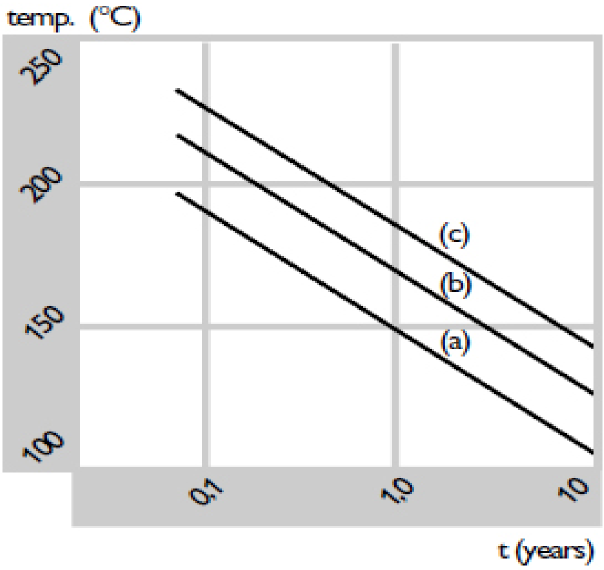


Fig. 37. The nominal life of choke coils in relation to the permitted rated maximum operating temperature of a ballast winding tw, dependent on insulation material:

a) class A: t_w 105°C,
b) class E: t_w 120°C,
c) class F or H: t_w 130°C.

It also takes some hours before the thermal equilibrium is reached in the ballast, which again increases the practical ballast lifetime. To verify the tw marking, accelerated lifetime tests are done at ballast temperatures above 200°C for 30 or 60 days.Another value marked on the ballast is the coil temperature rise Δt.This is the difference between the absolute coil temperature and the ambient temperature in standard conditions, and is measured by a method specified in IEC Publication 60922 (EN 60922). Common values for Δt are from 50 to 70 degrees in steps of 5 degrees. The coil temperature rise is measured by measuring the ohmic resistance of the cold and warm copper coil and using the formula:

$\Delta t = \{(R2 - R1)/R1\} \times (234.5 + t1) - (t2 - t1)$
or:
$\Delta tc = R2/R1 \times (t1 + 234.5) - 234.5$

where R1 = initial cold coil resistance in ohm (at start of measurement)
R2 = warm coil resistance in ohm (at end of measurement)
t2 = ambient temperature at measuring R2 in Celsius
t1 = ambient temperature at measuring R1 in Celsius
tc = calculated warm coil temperature in Celsius

$\Delta t = tc - t2$ in Kelvin

The value 234.5 applies to copper wire; in the case of aluminium wire, the value 229 should be used. So a ballast marked with tw 130 and Δt 70, will have the specified 10 years average life in continuous operation at standard conditions at an ambient temperature of 130°C - 70°C = 60°C.When the ambient temperature around the ballast is higher, a shorter ballast life has to be accepted, or sufficient air circulation or cooling has to be applied. The so-called ambient temperature mentioned in this section is not the room or outside temperature, but the temperature of the micro-environment of the ballast. Built into a luminaire or ballast box, the air temperature around the ballast is higher than the outside ambient temperature.This higher temperature has to be added to the coil temperature rise Δt to find the absolute coil temperature:

$tc = t2 + \Delta t$, (see fig. 38).

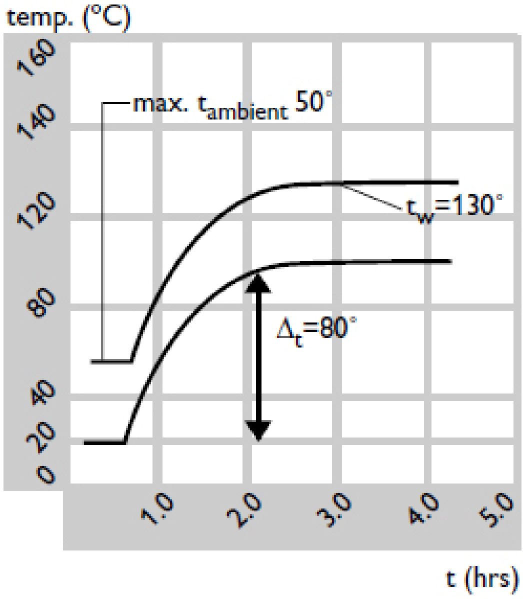


Fig. 38. Relation between tw , Δt and absolute ballast temperature.

Main ignitor functions and operation

Basically, there is only one function for an ignitor: to deliver the proper ignition voltage for starting the discharge in an HID lamp. But different ignitor types are required because different HID lamps require differing ignition voltages: the shape of the voltage peak, the number of voltage pulses within a certain period, the instant of application of the voltage itself, the amount of energy available and the amplitude, they all play a part in creating an optimum situation for establishing a discharge. Besides which, there are various ignition systems in use. After ignition the ignitor has to stop producing ignition peaks.This can be controlled by sensing the lamp voltage or lamp current and/or by a timer function. The voltage level at which an HID lamp will ignite is called its ignition voltage. In most lamp types special measures have been taken in the construction of the lamp to keep this ignition voltage as low as possible: the use of a starting gas as a Penning mixture (see Fig. 41) and the application of auxiliary electrodes to trigger the initial ionisation of the gas are examples of this. In the case of high-pressure mercury lamps, these measures are sufficient: these lamps will start on the mains voltage. Therefore, no separate ignitor is required and the ballast has no special function in the ignition process either. In other cases an internal glow-switch starter, built into the lamp, is sufficient to ignite the lamp, as with the lowwattage SON(-I) lamp.

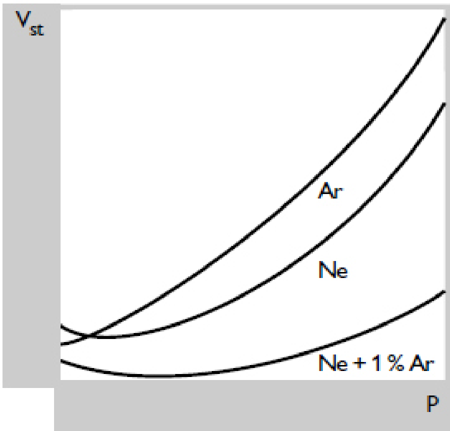


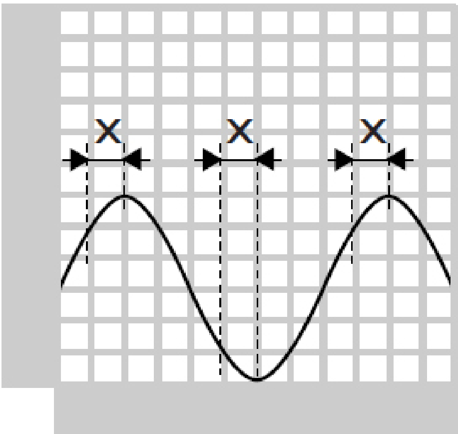
Fig. 41. Starting voltage curve: dependence of starting voltage (Vst) on gas pressure (p) for neon, argon and a mixture of the two.The addition of argon to neon clearly leads to a lower starting voltage level (Penning effect).

But all other types of HID lamps, including metal halide and low and high-pressure sodium lamps, require an external ignition device, either as an integral part of the ballast, or as an separate item of the control gear.This external ignition device must supply the voltage peaks necessary for starting the gas discharge. Mechanical switches such as relays or bi-metal switches may be used, but due to the high costs of replacement in outdoor applications, these have never become popular. Electronic ignitors prove to be the solution.They are based on the principle of a capacitor which is first charged via a diode and then discharged via a thyristor and so producing ignition peaks. When autoleak transformers are used as a ballast, a separate ignitor is not required, since the transformer already supplies the necessary starting voltage.

With cold lamps the required voltage pulses are of the order of 1kV to 5 kV, while the maximum permitted amplitude of the pulse is limited by the lamp construction and by the type of lampholder.The ignition takes place immediately after the ignition pulse occurs.
Required minimum and maximum peak voltages:

HPL 50-1000 W	0,3 kV
HPI 250-2000 W	0,6...1,4 kV
SOX 35-90 W	0,7...1 kV
SOX 135-180 W	0,7...1,4 kV
SON (CDM-TT) 50-70 W	1,8...2,5 kV
SON 100-1000 W	2,8...5,0 kV
CDM/MH 35..2000 W	3,2...5,0 kV

Apart from the peak amplitude also the peak width, the number of peaks and the position of the pulse in the mains sine wave are important, see for example Fig. 42.



In the marked areas 'X' lamp voltage is high enough to take over the lamp current after ionisation (typical position 30-90 degrees.)

Fig. 42. Pulse position for reliable ignition.

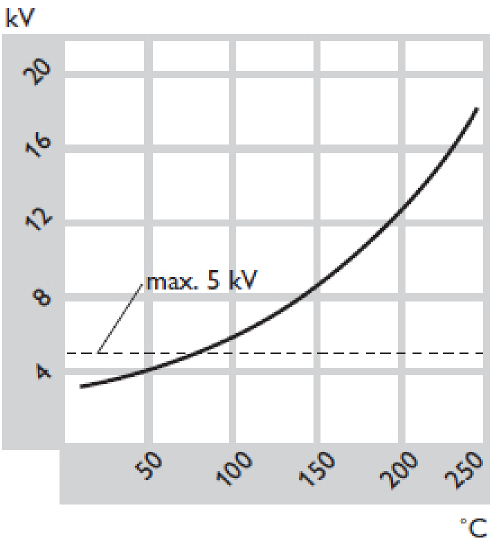


Fig. 43. Ignition voltage required for a typical high-pressure mercury lamp as a function of lamp temperature.

In the case of hot lamps (see Fig. 43) that have extinguished because of a power failure, accelerated ignition is possible at a certain stage as the lamps cool down. Hot metal halide lamps, for example, restart after 5 to 15 minutes and high-pressure sodium lamps without bi-metal after about 1 minute.The ignitors used in the hybrid circuit of SOX lamps enable the lamps to restart immediately when they are still warm. To restrike hot HID lamps, peak voltages of between 20 kV and 70 kV (depending on lamp type) are necessary. These peak voltages are produced by the Hot Restrike device, which in fact is just a special ignitor. HR devices, are available on the market.The ballasts and compensating capacitors are the same in standard and HR circuits.The difference is that the lamp, lampholder, lamp cabling and luminaire must be able to stand the high ignition voltages.This means employing a double ended lamp (no Edison fitting) and ensuring that there are sufficient creepage and clearance distances in the luminaire. HR devices stop producing the high ignition peaks when the lamp is ignited or, by use of a timer, after a few seconds.The wiring diagram differs from that of standard ignitors. Not only the lamp-HR device combination, but also the applied luminaire must be released for the HR application.

Ignitor types

In principle, there are three different types of ignitors or ignition systems:
semi-parallel, series and (full) parallel.

Semi-parallel (impulser) type ignitors

The preferred type of Sololuce ignitors are of the semiparallel impulser type .This means that one ignitor terminal is connected to a ballast tapping . In this way the ballast acts as a voltage transformer to create the high ignition voltage. It is therefore essential to use the ignitor in combination with a properly tapped ballast.With this type of ignition the ballast coil is exposed to the high pulse voltage and must have sufficient insulation quality to withstand the high voltage energy. By making use of the ballast coil instead of a separate ignitor coil (as described below) with the series ignitor, the total system of ballast and ignitor can be cheaper and the ignition pulse has a higher energy content, which results in more reliable ignition.

Series or Superimposed pulse type ignitors

The second family of ignitors is of the superimposed pulse type . Here the high voltage peak is generated in a separate transformer in the series ignitor .The ballast therefore has no ignitor tap and the coil is not exposed to the high pulse voltage peak and so the ballast can be cheaper. Nevertheless, the total system (ballast and ignitor) may be more expensive than the semi-parallel system.This is because the lamp current is passing through the ignitor, resulting in higher watt losses and possible hum, also during stable operation. In general this type of ignitor has to be mounted close to the lamp.

Parallel ignitors

The third group of ignitors is called parallel ignitors , as the ignitor is connected directly across the lamp .The ballast has no extra ignition function. No high peak voltages can be created by this system (typical 500-750 V for HPI-T, maximum 1500 V for BSX 180) and so the ballast is not exposed to high voltages.

Self-stopping ignitors

Standard ignitors keep on functioning when the lamp is not ignited, when the lamp is defective or when the lamp is cycling. During the lifetime of SON, MH and CDM lamps, the lamp voltage will rise, depending on the lamp type with, by between 1 and 4 volt per 1000 burning hours.At a certain moment, the available mains voltage will be too low for stable operation and the lamp will extinguish. But after cooling down, the lamp will restart again, runs up to its high lamp voltage, and again extinguish.This repeating sequence is called cycling. In normal situations the effective ignition time of the ignitor is very short, but in the cycling situation the effective ignition time is extended dramatically. This can lead to early ballast and/or ignitor failures. Therefore self-stopping versions, which stop after 5 or 15 minutes, are available to avoid the cycling behaviour (see Fig. 44) at the end of lamp life .

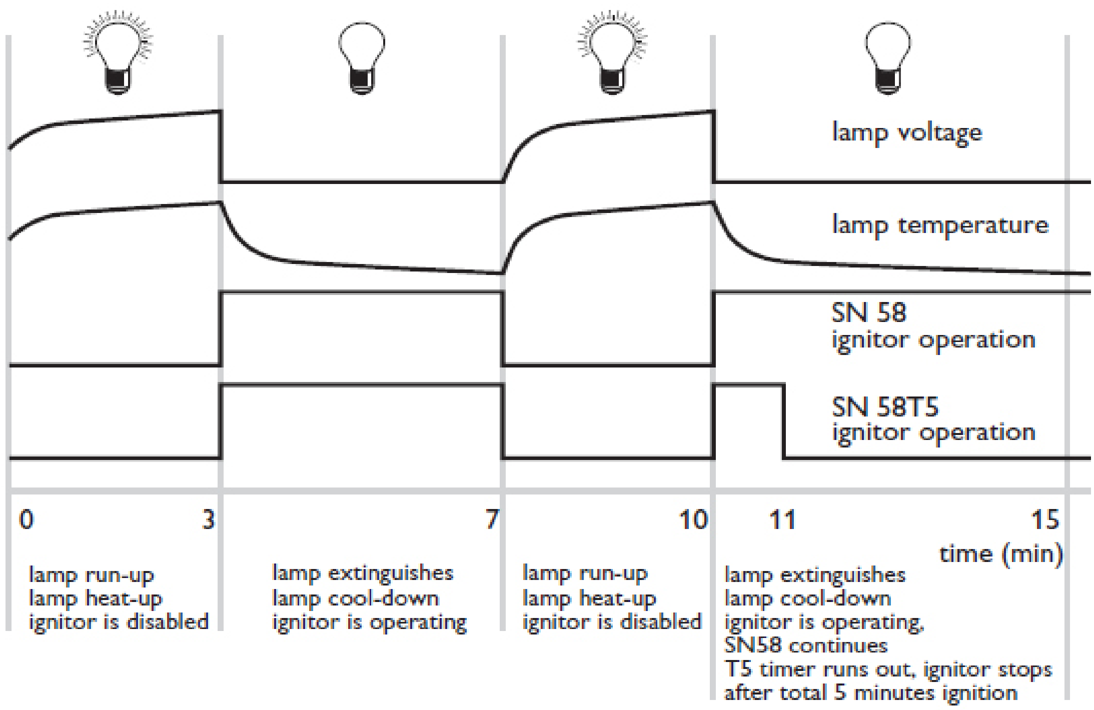


Fig. 44. Cycling behaviour at the end of lamp life with a normal and a self-stopping ignitor.

The operation of the ignitors is controlled by the lamp voltage. Counting down from the minutes indicated by the number after the T, the timer holds as soon as the lamp has ignited, whilst the remaining time is retained in the memory.The memory function has been implemented to allow for re-ignition if the lamp extinguishes as a result of temporary voltage dips. Consequently, these ignitors are resistant to voltage dips within the timer setting. Resetting the mains supply (disconnecting) for a minimum of 20 seconds is necessary to be able to again restart with the full ignition time available.

Reasons for applying self-stopping ignitors:

- no annoying cycling, and so reduction of radio interference,
- reduced risk of creating of the DC-current, which leads to possible overheating of the ballast,
- prolonged lifetime of ignitor.

Comparison between semi-parallel and superimposed (series) ignition systems

For the ignition of lamps such as high-pressure sodium or metal halide lamps, the choice basically exists between two systems previously mentioned namely:

- semi-parallel, IMP, also called impulser (see Fig. 45) or
- superimposed pulse, SIP, also called series (see Fig. 46).

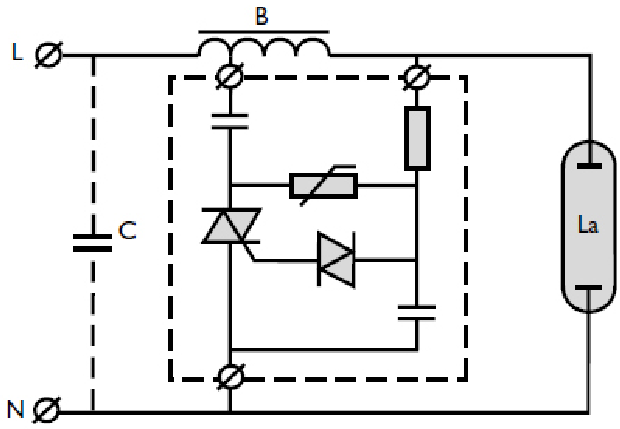


Fig. 45. Semi-parallel ignition system.
La = lamp
B = ballast
C = capacitor

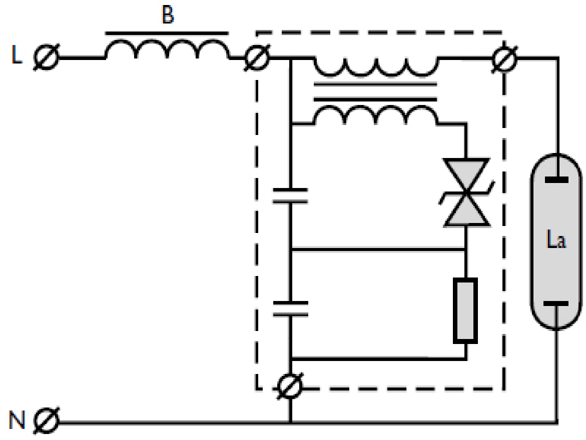


Fig. 46. Superimposed ignition system.
La = lamp
B = ballast

The semi-parallel system is an arrangement in which the ballast and ignitor form a matched pair: the one cannot operate without the other.The ignitor uses the ballast to generate the ignition pulse for the lamp. The series ignitor works more or less without the ballast. In many cases the two systems are seen as being interchangeable. However, when they are closely compared, a number of differences become evident:

1. During normal lamp operation, the semi-parallel ignitor is no longer part of the current-carrying section of the electrical circuit.This implies that the ignitor does not consume any power and is therefore not self-heating.The series ignitor, on the other hand, is connected in series with the lamp and so always consumes some power.

2. Because the semi-parallel ignitor uses the ballast to generate the ignition pulse, it can fulfil this task very effectively.This high energy content ensures reliable lamp ignition. Furthermore, it permits of considerable distances between ballast/ignitor and lamp, so enabling the gear to be located more remotely: distances of 20 m, under nominal conditions, are no exception. The series ignitor produces smaller ignition peaks with less energy and must be connected close to the lamp.

3.As the semi-parallel ignitor is making use of the ballast to generate the ignition pulse, it contains no transformer.This means that there are no components inside the ignitor, that could otherwise cause irritating hum in the longer term. For indoor applications in particular this is an important consideration. The series ignitor makes use of a transformer in series with the lamp.

4. Some lamps can display a rectifying effect towards the end of their technical life. Metal halide lamps, more than high-pressure sodium types, tend to exhibit this, but there is always a chance of occurrence.A semiparallel ignitor is not connected in the current-carrying section of the circuit and will therefore not be affected by this phenomenon. Series ignitors will be damaged by the DC current, unless special precautions are taken.

For lamp types that do exhibit rectifying effects at the end of life, so-called thermo-switch ballasts are recommended, because the built-in thermo-switch will then protect the ballast from any hazardous lamp behaviour Hence, when a thermo-switch ballast is required, it is advisable to employ a self-stopping semi-parallel ignitor system. In this way, maximum circuit protection can be assured.
5.Also from a commercial point of view too, the semiparallel system offers many benefits. In principle, the ignitor is power-independent: one ignitor can be used for a large number of lamps.This results in logistical advantages as well as financial gain (especially with higher wattage circuits) since the price of the ignitor does not rise with increasing lamp wattage. It should be noted, by the way, that a perception exists that in the semi-parallel system the ballast might be destroyed should the lamp does not ignite (for whatever reason).The ignition pulse would adversely affect the ballast and ultimately destroy it. However, in practice, there is however no noticeable difference between the performance of the semi-parallel system and the superimposed system. In the semi-parallel circuit, the ballast is stressed by the ignition pulse, whilst in the superimposed circuit the ignitor is stressed. But all components are developed and constructed to withstand this situation.

Lifetime

Under normal conditions, an ignitor actually operates for only a few cycles, once every day, when the lights are switched on.The ignitor case temperature at this time is the ambient temperature. Under these conditions, the actual ignitor life expended is insignificant (less than one second per day, see Fig. 47). Even if the lights were turned off momentarily, once each day, it requires only about one minute of pulsing by the ignitor to re-ignite the lamp.Assuming an ignitor case temperature of 90°C (worst case), an operating period of one minute per day would total to only about five hours of actual operation per year. Since average ignitor life at 90°C is 800 hours, the use of five hours per year is only an insignificant portion of the total lifetime.

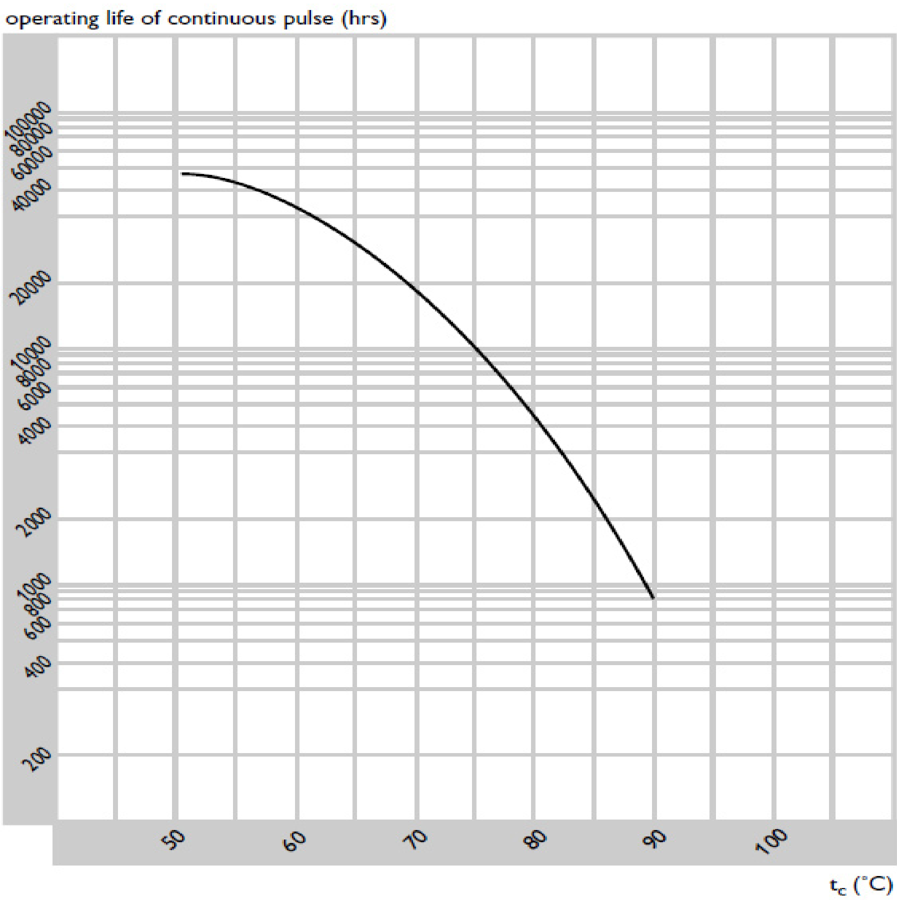


Fig. 47. Estimated operating life of ignitors as a function of case temperature.

On the other hand, ignitor life can be used up at a significant rate when an inoperative lamp remains in an energised socket for extended periods of time. In this instance, the ignitor may be pulsing from 8 to 24 hours per day, depending on the lighting application.

Experience has shown that ignitor case temperatures typically run about 15°C above the luminaire ambient temperature.Assuming a very severe application with a 75°C case temperature, a total of 10 000 hours of proper functioning can be expected. If, however, the ignitor were pulsing 24 hours per day (i.e. continuously), this would result in a shorter ignitor life.The ignitors are specified for 30 days, but tested for 60 days continuous operation. The situation is slightly different with series ignitors, as the transformer coil is stressed by the lamp current. Although the specification is the same for series and semi-parallel ignitors, in some applications the series ignitor is replaced together with the defective lamp.