Gas Discharge Power Sources & Devices

(Artificial Light)

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Gas-Discharge Lamp

Germicidal lamps are simple low pressure mercury vapor discharges in a fused quartz envelope.

Gas-discharge lamps are a family of artificial light sources that generate light by sending an electrical discharge through an ionized gas, i.e. a plasma. The character of the gas discharge critically depends on the frequency or modulation of the current: the entry on a frequency classification of plasmas. Typically, such lamps use a noble gas (argon, neon, krypton and xenon) or a mixture of these gases. Most lamps are filled with additional materials, like mercury, sodium, and/or metal halides. In operation the gas is ionized, and free electrons, accelerated by the electrical field in the tube, collide with gas and metal atoms. Some electrons in the atomic orbitals of these atoms are excited by these collisions to a higher energy state. When the excited atom falls back to a lower energy state, it emits a photon of a characteristic energy, resulting in infrared, visible light, or ultraviolet radiation. Some lamps will convert the ultraviolet radiation to visible light with a fluorescent coating on the inside of the lamp's glass surface. The fluorescent lamp is perhaps the best known gas-discharge lamp.

Gas-discharge lamps offer long life and high efficiency, but are more complicated to manufacture, and they require electronics to provide the correct current flow through the gas.

History

The history of gas-discharge lamps began in 1675 when French astronomer Jean-Felix Picard observed that the empty space in his mercury barometer glowed as the mercury jiggled while he was carrying the barometer. Investigators, including Francis Hauksbee, tried to determine the cause of the phenomenon. Hauksbee first demonstrated a gas-discharge lamp in 1705. He showed that an evacuated or partially evacuated glass globe, while charged by static electricity could produce a light bright enough to read by. The phenomenon of electric arc was first described by Vasily V. Petrov, a Russian scientist, in 1802; Sir Humphry Davy demonstrated in the same year the electric arc at the Royal Institution of Great Britain. Since then, discharge light sources have been researched because they create light from electricity considerably more efficiently than incandescent light bulbs.

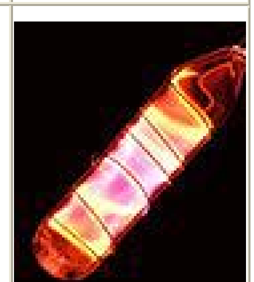
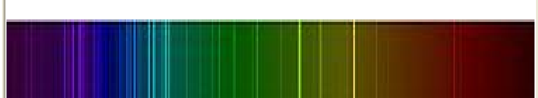
Later it was discovered that the arc discharge could be optimized by using an inert gas instead of air as a medium. Therefore noble gases neon, argon, krypton or xenon were used, as well as carbon dioxide historically.

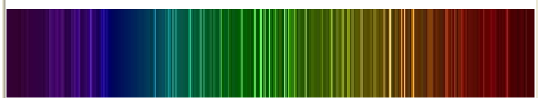
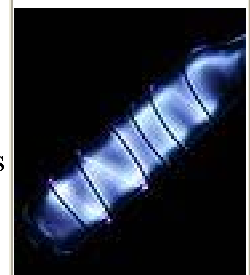
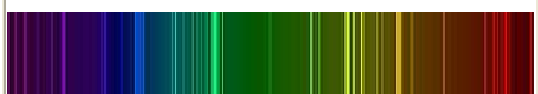
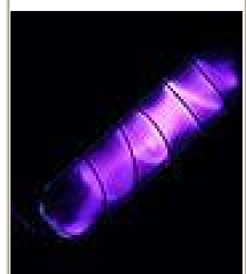
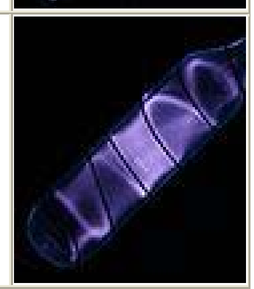
The introduction of the metal vapor lamp, including various metals within the discharge tube, was a later advance. The heat of the gas discharge vaporized some of the metal and the discharge is then produced almost exclusively by the metal vapor. The usual metals are sodium and mercury owing to their high vapor pressures that increase efficiency of visible spectrum emission.

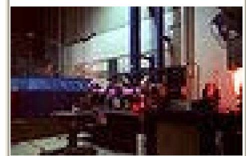
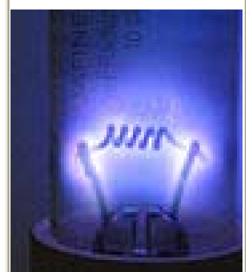
One hundred years of research later led to lamps without electrodes which are instead energized by microwave or radio frequency sources. In addition, light sources of much lower output have been created, extending the applications of discharge lighting to home or indoor use.

Color

Each gas, depending on its atomic structure emits certain wavelengths which translates in different colors of the lamp. As a way of evaluating the ability of a light source to reproduce the colors of various objects being lit by the source, the International Commission on Illumination (CIE) introduced the color rendering index. Some gas-discharge lamps have a relatively low CRI, which means colors they illuminate appear substantially different than they do under sunlight or other high-CRI illumination.

Gas	Color	Spectrum	Notes	Image
Helium	White to orange; under some conditions may be gray, blue, or green-blue.		Used by artists for special purpose lighting.	
Neon	Red-orange		Intense light. Used frequently in neon signs and neon lamps.	
Argon	Violet to pale lavender blue		Often used together with mercury vapor.	
Krypton	Gray off-white to green. At high peak currents, bright blue-		Used by artists for special purpose lighting.	

	white.			
Xenon	Gray or blue-gray dim white. At high peak currents, very bright green-blue.		Used in flashbulbs, xenon HID headlamps, and xenon arc lamps.	
Nitrogen	Similar to argon but duller, more pink; at high peak currents bright blue-white.			
Oxygen	Violet to lavender, dimmer than argon			
Hydrogen	Lavender at low currents, pink to magenta over 10 mA			
Water vapor	Similar to hydrogen, dimmer			

Carbon dioxide	Blue-white to pink, in lower currents brighter than xenon		Used in Carbon Dioxide Lasers.	
Mercury vapor	Light blue, intense ultraviolet	 Ultraviolet not shown	In combination with phosphors used to generate many colors of light. Widely used in mercury-vapor lamps.	
Sodium vapor (low pressure)	Bright orange-yellow		Widely used in sodium vapor lamps.	

Most common gas-discharge lamps

Low pressure discharge lamps

A Compact fluorescent lamp

Low-pressure lamps have working pressure much less than atmospheric pressure.

- Fluorescent lamps, the most common lamp in office lighting and many other applications, produces up to 100 lumens per watt
- Low pressure sodium lamps, the most efficient gas-discharge lamp type, producing up to 200 lumens per watt, but at the expense of very poor color

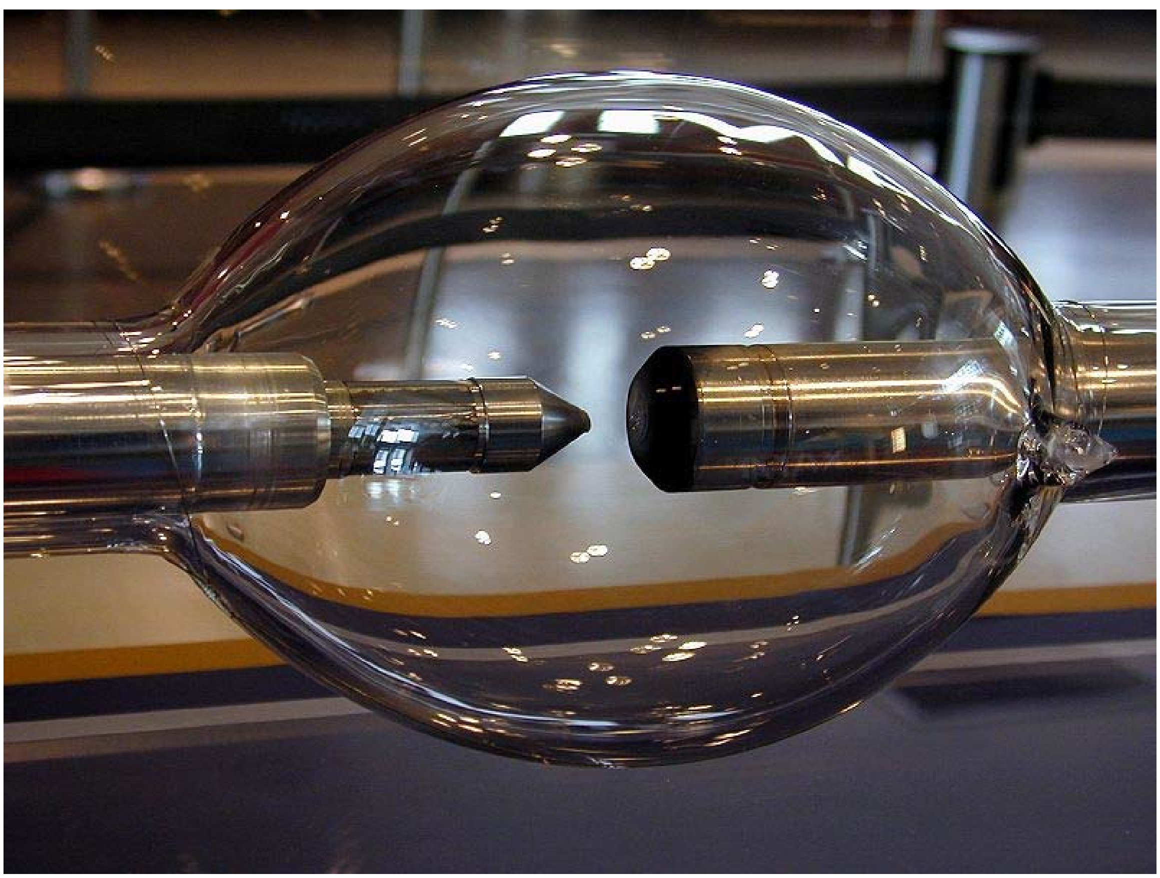
rendering. The almost monochromatic yellow light is only acceptable for street lighting and similar applications.

High pressure discharge lamps

High-pressure lamps have a discharge that takes place in gas under slightly less to greater than atmospheric pressure. For example, a high pressure sodium lamp has an arc tube under 100 to 200 torr pressure, about 14% to 28% of atmospheric pressure; some automotive HID headlamps have up to 50 bar or fifty times atmospheric prssure.

- Metal halide lamps. These lamps produce almost white light, and attain 100 lumen per watt light output. Applications include indoor lighting of high buildings, parking lots, shops, sport terrains.
- High pressure sodium lamps, producing up to 150 lumens per watt. These lamps produce a broader light spectrum than the low pressure sodium lamps. Also used for street lighting, and for artificial photoassimilation for growing plants
- High pressure mercury-vapor lamps. This lamp type is the oldest high pressure lamp type, being replaced in most applications by the metal halide lamp and the high pressure sodium lamp.

High-intensity discharge lamps



15 kW xenon short-arc lamp used in IMAX projectors

A high-intensity discharge (HID) lamp is a type of electrical lamp which produces light by means of an electric arc between tungsten electrodes housed inside a translucent or transparent fused quartz or fused alumina arc tube. Compared to other lamp types, relatively high arc power exists for the arc length. Examples of HID lamps include:

- Mercury-vapor lamps
- Metal halide lamps
- Ceramic discharge metal halide lamps
- Sodium vapor lamps
- Xenon arc lamps
- Ultra-High Performance (UHP)

HID lamps are typically used when high levels of light over large areas are required, and when energy efficiency and/or light intensity are desired.

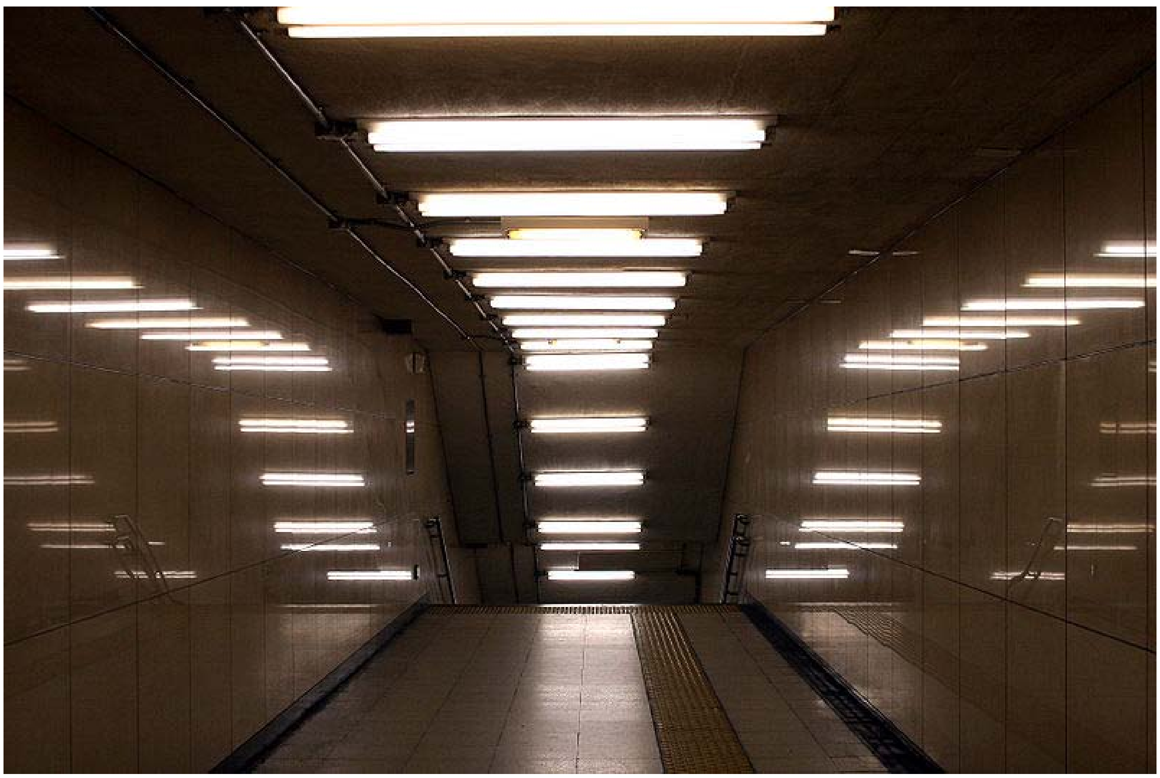
Other examples

- Neon signs may use either direct illumination or, to obtain certain colors, indirect phosphor excitation.

- Xenon flash lamp. This lamp is commonly found in film and digital cameras, even in single-use cameras. These lamps have produced interesting illumination effects in theatre and dancing. More robust versions of this lamps, known as strobe lights, can produce short intense flashes repeatedly, allowing the stroboscopic examination of repetitive motion (useful in certain balancing applications). These were at one time popular, "freezing" the motion of the actors or dancers. This type of lamp was also used to demonstrate persistence of vision, where an entire room would be illuminated by multiple lamps behind diffusing wall panels. In this otherwise darkened room a periodic flash would cause every detail of the occupants to be imaged on the observer's retina, completely frozen in motion.

Chapter- 2

Fluorescent Lamp



Fluorescent lamps

Assorted types of fluorescent lamps. Top, two compact fluorescent lamps. Bottom, two regular tubes. Left, matchstick shown for scale.

Typical F71T12 100 W bi-pin lamp used in tanning beds. Note the (Hg) symbol indicating it contains mercury. In the US this symbol is now required on all fluorescent bulbs that contain mercury.

A **fluorescent lamp** or **fluorescent tube** is a gas-discharge lamp that uses electricity to excite mercury vapor. The excited mercury atoms produce short-wave ultraviolet light that then causes a phosphor to fluoresce, producing visible light. A fluorescent lamp converts electrical power into useful light more efficiently than an incandescent lamp. Lower energy cost typically offsets the higher initial cost of the lamp. The lamp fixture is more costly because it requires a ballast to regulate the current through the lamp.

While larger fluorescent lamps have been mostly used in commercial or institutional buildings, the compact fluorescent lamp is now available in the same popular sizes as incandescents and is used as an energy-saving alternative in homes.

History

Physical discoveries

Fluorescence of certain rocks and other substances had been observed for hundreds of years before its nature was understood. By the middle of the 19th century, experimenters had observed a radiant glow emanating from partially evacuated glass vessels through which an electrical current passed. One of the first to explain it was the Irish scientist Sir George Stokes from the University of Cambridge, who named the phenomenon "fluorescence" after fluorite, a mineral many of whose samples fluoresce strongly due to impurities. The explanation relied on the nature of electricity and light phenomena as developed by the British scientists Michael Faraday and James Clerk Maxwell in the 1840s.

Little more was done with this phenomenon until 1856 when a German glassblower named Heinrich Geissler created a mercury vacuum pump that evacuated a glass tube to an extent not previously possible. When an electrical current passed through a Geissler tube, a strong green glow on the walls of the tube at the cathode end could be observed. Because it produced some beautiful light effects, the Geissler tube was a popular source of amusement. More important, however, was its contribution to scientific research. One of the first scientists to experiment with a Geissler tube was Julius Plücker who systematically described in 1858 the luminescent effects that occurred in a Geissler tube. He also made the important observation that the glow in the tube shifted position when in proximity to an electromagnetic field. Alexandre Edmond Becquerel observed in 1859 that certain substances gave off light when they were placed in a Geissler tube. He went on to apply thin coatings of luminescent materials to the surfaces of these tubes. Fluorescence occurred, but the tubes were very inefficient and had a short operating life.

Inquiries that began with the Geissler tube continued as even better vacuums were produced. The most famous was the evacuated tube used for scientific research by William Crookes. That tube was evacuated by the highly effective mercury vacuum pump created by Hermann Sprengel. Research conducted by Crookes and others ultimately led to the discovery of the electron in 1897 by J. J. Thomson. But the Crookes tube, as it came to be known, produced little light because the vacuum in it was too good and thus lacked the trace amounts of gas that are needed for electrically stimulated luminescence.

Early discharge lamps

While Becquerel was primarily interested in conducting scientific research into fluorescence, Thomas Edison briefly pursued fluorescent lighting for its commercial potential. He invented a fluorescent lamp in 1896 that used a coating of calcium tungstate as the fluorescing substance, excited by X-rays, but although it received a patent in 1907, it was not put into production. As with a few other attempts to use Geissler tubes for illumination, it had a short operating life, and given the success of the incandescent light, Edison had little reason to pursue an alternative means of electrical illumination. Nikola Tesla made similar experiments in the 1890s, devising high frequency powered fluorescent bulbs that gave a bright greenish light, but as with Edison's devices, no commercial success was achieved.

Although Edison lost interest in fluorescent lighting, one of his former employees was able to create a gas-based lamp that achieved a measure of commercial success. In 1895

Daniel McFarlan Moore demonstrated lamps 2 to 3 meters (6.6 to 9.8 ft) in length that used carbon dioxide or nitrogen to emit white or pink light, respectively. As with future fluorescent lamps, they were considerably more complicated than an incandescent bulb.

After years of work, Moore was able to extend the operating life of the lamps by inventing an electromagnetically controlled valve that maintained a constant gas pressure within the tube. Although Moore's lamp was complicated, expensive to install, and required very high voltages, it was considerably more efficient than incandescent lamps, and it produced a more natural light than incandescent lamps. From 1904 onwards Moore's lighting system was installed in a number of stores and offices. Its success contributed to General Electric's motivation to improve the incandescent lamp, especially its filament. GE's efforts came to fruition with the invention of a tungsten-based filament. The extended lifespan of incandescent bulbs negated one of the key advantages of Moore's lamp, but GE purchased the relevant patents in 1912. These patents and the inventive efforts that supported them were to be of considerable value when the firm took up fluorescent lighting more than two decades later.

At about the same time that Moore was developing his lighting system, another American was creating a means of illumination that also can be seen as a precursor to the modern fluorescent lamp. This was the mercury-vapor lamp, invented by Peter Cooper Hewitt and patented in 1901 (US 682692)(Note: This patent number is universally misquoted as US889,692). Hewitt's lamp luminesced when an electric current was passed through mercury vapor at a low pressure. Unlike Moore's lamps, Hewitt's were manufactured in standardized sizes and operated at low voltages. The mercury-vapor lamp was superior to the incandescent lamps of the time in terms of energy efficiency, but the blue-green light it produced limited its applications. It was, however, used for photography and some industrial processes.

Mercury vapor lamps continued to be developed at a slow pace, especially in Europe, and by the early 1930s they received limited use for large-scale illumination. Some of them employed fluorescent coatings, but these were primarily used for color correction and not for enhanced light output. Mercury vapor lamps also anticipated the fluorescent lamp in their incorporation of a ballast to maintain a constant current.

Cooper-Hewitt had not been the first to use mercury vapor for illumination, as earlier efforts had been mounted by Way, Rapieff, Arons, and Bastian and Salisbury. Of particular importance was the mercury vapor lamp invented by Küch in Germany. This lamp used quartz in place of glass to allow higher operating temperatures, and hence greater efficiency. Although its light output relative to electrical consumption was better than other sources of light, the light it produced was similar to that of the Cooper-Hewitt lamp in that it lacked the red portion of the spectrum, making it unsuitable for ordinary lighting.

Neon lamps

The next step in gas-based lighting took advantage of the luminescent qualities of neon, an inert gas that had been discovered in 1898 by isolation from the atmosphere. Neon glowed a brilliant red when used in Geissler tubes. By 1910, Georges Claude, a Frenchman who had developed a technology and a successful business for air liquefaction, was obtaining enough neon as a byproduct to support a neon lighting industry. While neon lighting was used around 1930 in France for general illumination, it was no more energy-efficient than conventional incandescent lighting. Neon tube lighting, which also includes the use of argon and mercury vapor as alternate gases, came to be used primarily for eye-catching signs and advertisements. Neon lighting was relevant to the development of fluorescent lighting, however, as Claude's improved electrode (patented in 1915) overcame "sputtering", a major source of electrode degradation. Sputtering occurred when ionized particles struck an electrode and tore off bits of metal. Although Claude's invention required electrodes with a lot of surface area, it showed that a major impediment to gas-based lighting could be overcome.

The development of the neon light also was significant for the last key element of the fluorescent lamp, its fluorescent coating. In 1926 Jacques Risler received a French patent for the application of fluorescent coatings to neon light tubes. The main use of these lamps, which can be considered the first commercially successful fluorescents, was for advertising, not general illumination. This, however, was not the first use of fluorescent coatings. As has been noted above, Edison used calcium tungstate for his unsuccessful lamp. Other efforts had been mounted, but all were plagued by low efficiency and various technical problems. Of particular importance was the invention in 1927 of a low-voltage "metal vapor lamp" by Friedrich Meyer, Hans-Joachim Spanner, and Edmund Germer, who were employees of a German firm in Berlin. A German patent was granted but the lamp never went into commercial production.

Commercialization of fluorescent lamps

All the major features of fluorescent lighting were in place at the end of the 1920s. Decades of invention and development had provided the key components of fluorescent lamps: economically manufactured glass tubing, inert gases for filling the tubes, electrical ballasts, long-lasting electrodes, mercury vapor as a source of luminescence, effective means of producing a reliable electrical discharge, and fluorescent coatings that could be energized by ultraviolet light. At this point, intensive development was more important than basic research.

In 1934, Arthur Compton, a renowned physicist and GE consultant, reported to the GE lamp department on successful experiments with fluorescent lighting at General Electric Co., Ltd. in Great Britain (unrelated to General Electric in the United States). Stimulated by this report, and with all of the key elements available, a team led by George E. Inman built a prototype fluorescent lamp in 1934 at General Electric's Nela Park (Ohio) engineering laboratory. This was not a trivial exercise; as noted by Arthur A. Bright, "A great deal of experimentation had to be done on lamp sizes and shapes, cathode construction, gas pressures of both argon and mercury vapor, colors of fluorescent powders, methods of attaching them to the inside of the tube, and other details of the lamp and its auxiliaries before the new device was ready for the public."

In addition to having engineers and technicians along with facilities for R&D work on fluorescent lamps, General Electric controlled what it regarded as the key patents covering fluorescent lighting, including the patents originally issued to Hewitt, Moore, and Küch. More important than these was a patent covering an electrode that did not disintegrate at the gas pressures that ultimately were employed in fluorescent lamps. Albert W. Hull of GE's Schenectady Research Laboratory filed for a patent on this invention in 1927, which was issued in 1931.

While the Hull patent gave GE a basis for claiming legal rights over the fluorescent lamp, a few months after the lamp went into production the firm learned of a U.S. patent application that had been filed in 1927 for the aforementioned "metal vapor lamp" invented in Germany by Meyer, Spanner, and Germer. The patent application indicated that the lamp had been created as a superior means of producing ultraviolet light, but the application also contained a few statements referring to fluorescent illumination. Efforts to obtain a U.S. patent had met with numerous delays, but were it to be granted, the patent might have caused serious difficulties for GE. At first, GE sought to block the issuance of a patent by claiming that priority should go to one of their employees, Leroy J. Buttolph, who according to their claim had invented a fluorescent lamp in 1919 and whose patent application was still pending. GE also had filed a patent application in 1936 in Inman's name to cover the "improvements" wrought by his group. In 1939 GE decided that the claim of Meyer, Spanner, and Germer had some merit, and that in any event a long interference procedure was not in their best interest. They therefore dropped the Buttolph claim and paid $180,000 to acquire the Meyer, et al. application, which at that point was owned by a firm known as Electrons, Inc. The patent was duly awarded in December 1939. This patent, along with the Hull patent, put GE on what seemed to be firm legal ground, although it faced years of legal challenges from Sylvania Electric Products, Inc., which claimed infringement on patents that it held.

Even though the patent issue would not be completely resolved for many years, General Electric's strength in manufacturing and marketing the bulb gave it a pre-eminent position in the emerging fluorescent light market. Sales of "fluorescent lumiline lamps" commenced in 1938 when four different sizes of tubes were put on the market used in fixtures manufactured by three leading corporations, two based in New York City. During the following year GE and Westinghouse publicized the new lights through exhibitions at the New York World's Fair and the Golden Gate International Exposition in San Francisco. Fluorescent lighting systems spread rapidly during World War II as wartime manufacturing intensified lighting demand. By 1951 more light was produced in the United States by fluorescent lamps than by incandescent lamps.

Principles of operation

The fundamental means for conversion of electrical energy into radiant energy in a fluorescent lamp relies on inelastic scattering of electrons. An incident electron collides with an atom in the gas. If the free electron has enough kinetic energy, it transfers energy to the atom's outer electron, causing that electron to temporarily jump up to a higher energy level. The collision is 'inelastic' because a loss of energy occurs.

This higher energy state is unstable, and the atom will emit an ultraviolet photon as the atom's electron reverts to a lower, more stable, energy level. Most of the photons that are released from the mercury atoms have wavelengths in the ultraviolet (UV) region of the spectrum, predominantly at wavelengths of 253.7 nm and 185 nm. These are not visible to the human eye, so they must be converted into visible light. This is done by making use of fluorescence. Ultraviolet photons are absorbed by electrons in the atoms of the lamp's interior fluorescent coating, causing a similar energy jump, then drop, with emission of a further photon. The photon that is emitted from this second interaction has a lower energy than the one that caused it. The chemicals that make up the phosphor are chosen so that these emitted photons are at wavelengths visible to the human eye. The difference in energy between the absorbed ultra-violet photon and the emitted visible light photon goes toward heating up the phosphor coating.

When the light is turned on, the electric power heats up the cathode enough for it to emit electrons. These electrons collide with and ionize noble gas atoms inside the bulb surrounding the filament to form a plasma by the process of impact ionization. As a result of avalanche ionization, the conductivity of the ionized gas rapidly rises, allowing higher currents to flow through the lamp.

Construction

Close-up of the cathodes of a germicidal lamp (an essentially similar design that uses no fluorescent phosphor, allowing the electrodes to be seen.)

A fluorescent lamp tube is filled with a gas containing low pressure mercury vapor and argon, xenon, neon, or krypton. The pressure inside the lamp is around 0.3% of atmospheric pressure. The inner surface of the bulb is coated with a fluorescent (and often slightly phosphorescent) coating made of varying blends of metallic and rare-earth phosphor salts. The bulb's electrodes are typically made of coiled tungsten and usually referred to as cathodes because of their prime function of emitting electrons. For this, they are coated with a mixture of barium, strontium and calcium oxides chosen to have a low thermionic emission temperature.

The unfiltered ultraviolet glow of a germicidal lamp is produced by a low pressure mercury vapor discharge (identical to that in a fluorescent lamp) in an uncoated fused quartz envelope.

Fluorescent lamp tubes are typically straight and range in length from about 100 millimeters (3.9 in) for miniature lamps, to 2.43 meters (8.0 ft) for high-output lamps. Some lamps have the tube bent into a circle, used for table lamps or other places where a more compact light source is desired. Larger U-shaped lamps are used to provide the same amount of light in a more compact area, and are used for special architectural purposes. Compact fluorescent lamps have several small-diameter tubes joined in a bundle of two, four, or six, or a small diameter tube coiled into a spiral, to provide a high amount of light output in little volume.

Light-emitting phosphors are applied as a paint-like coating to the inside of the tube. The organic solvents are allowed to evaporate, then the tube is heated to nearly the melting point of glass to drive off remaining organic compounds and fuse the coating to the lamp tube. Careful control of the grain size of the suspended phosphors is necessary; large grains, 35 micrometers or larger, lead to weak grainy coatings, whereas too many small particles 1 or 2 micrometers or smaller leads to poor light maintenance and efficiency. Most phosphors perform best with a particle size around 10 micrometers. The coating must be thick enough to capture all the ultraviolet light produced by the mercury arc, but not so thick that the phosphor coating absorbs too much visible light. The first phosphors were synthetic versions of naturally occurring fluorescent minerals, with small amounts of metals added as activators. Later other compounds were discovered, allowing differing colors of lamps to be made.

Electrical aspects of operation

Different ballasts for fluorescent and discharge lamps

Fluorescent lamps are negative differential resistance devices, so as more current flows through them, the electrical resistance of the fluorescent lamp drops, allowing even more current to flow. Connected directly to a constant-voltage power supply, a fluorescent lamp would rapidly self-destruct due to the uncontrolled current flow. To prevent this, fluorescent lamps must use an auxiliary device, a ballast, to regulate the current flow through the tube.

The terminal voltage across an operating lamp varies depending on the arc current, tube diameter, temperature, and fill gas. A fixed part of the voltage drop is due to the electrodes. A general lighting service T12 48 inch (1200 mm) lamp operates at 430 mA, with 100 volts drop. High output lamps operate at 800 mA, and some types operate up to 1500 mA. The power level varies from 10 watts per foot (33 watts per meter) to 25 watts per foot (82 watts per meter) of tube length for T12 lamps.

The simplest ballast for alternating current use is an inductor placed in series, consisting of a winding on a laminated magnetic core. The inductance of this winding limits the flow of AC current. This type is still used, for example, in 120 volt operated desk lamps using relatively short lamps. Ballasts are rated for the size of lamp and power frequency. Where the mains voltage is insufficient to start long fluorescent lamps, the ballast is often a step-up autotransformer with substantial leakage inductance (so as to limit the current flow). Either form of inductive ballast may also include a capacitor for power factor correction.

230 V ballast for 18–20 W

Many different circuits have been used to operate fluorescent lamps. The choice of circuit is based on mains voltage, tube length, initial cost, long term cost, instant versus non-instant starting, temperature ranges and parts availability, etc.

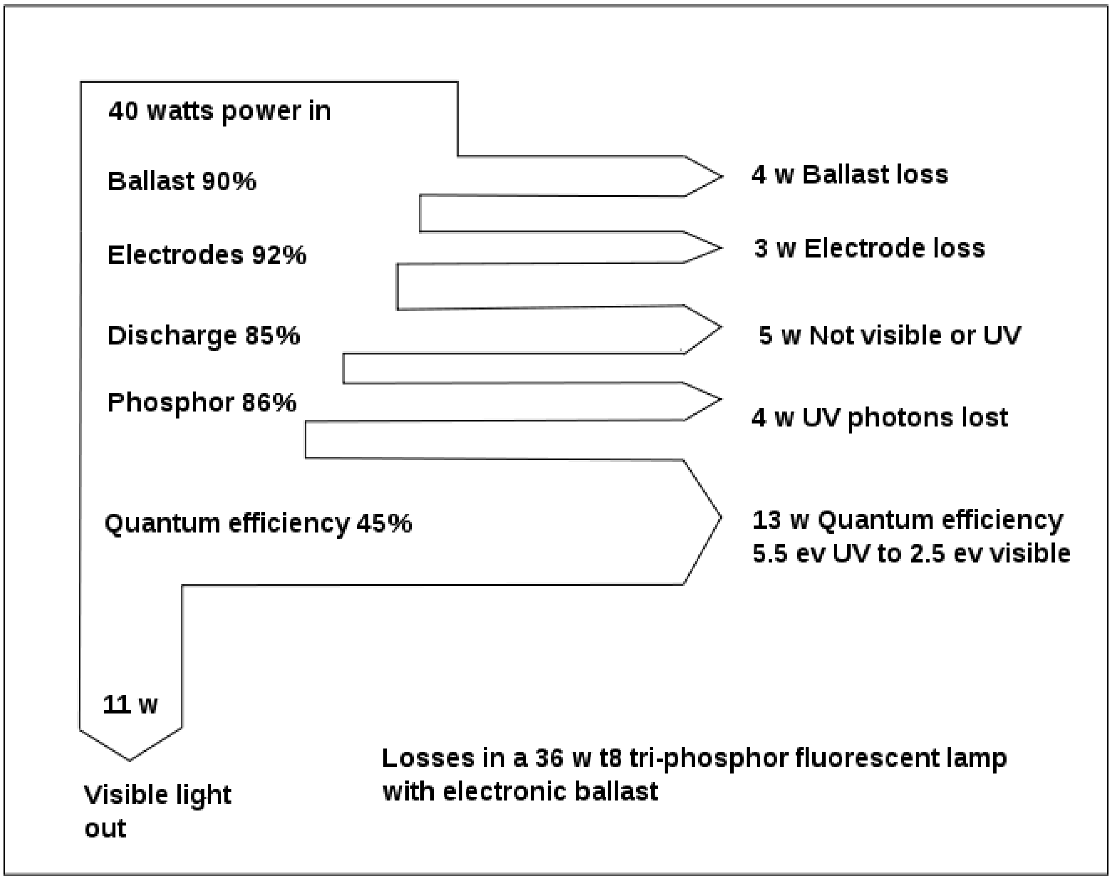
Fluorescent lamps can run directly from a DC supply of sufficient voltage to strike an arc. The ballast must be resistive, and would consume about as much power as the lamp. When operated from DC, the starting switch is often arranged to reverse the polarity of the supply to the lamp each time it is started; otherwise, the mercury accumulates at one end of the tube. Fluorescent lamps are (almost) never operated directly from DC for those reasons. Instead, an inverter converts the DC into AC and provides the current-limiting function as described below for electronic ballasts.

Effect of temperature

The light output and performance of fluorescent lamps is critically affected by the temperature of the bulb wall and its effect on the partial pressure of mercury vapor within the lamp. Each lamp contains a small amount of mercury, which must vaporize to support the lamp current and generate light. At low temperatures the mercury is in the form of dispersed liquid droplets. As the lamp warms, more of the mercury is in vapor form. At higher temperatures, self-absorption in the vapor reduces the yield of UV and visible light. Since mercury condenses at the coolest spot in the lamp, careful design is required to maintain that spot at the optimum temperature, around 40 °C.

By using an amalgam with some other metal, the vapor pressure is reduced and the optimum temperature range extended upward; however, the bulb wall "cold spot" temperature must still be controlled to prevent migration of the mercury out of the amalgam and condensing on the cold spot. Fluorescent lamps intended for higher output will have structural features such as a deformed tube or internal heat-sinks to control cold spot temperature and mercury distribution. Heavily loaded small lamps, such as compact fluorescent lamps, also include heat-sink areas in the tube to maintain mercury vapor pressure at the optimum value.

Losses



A Sankey diagram of energy losses in a fluorescent lamp. In modern designs, the biggest loss is the quantum efficiency of converting high-energy UV photons to lower-energy visible light photons.

The efficiency of fluorescent lighting owes much to the fact that low pressure mercury discharges emit about 65% of their total light in the 254 nm line (another 10–20% of the light is emitted in the 185 nm line). The UV light is absorbed by the bulb's fluorescent coating, which re-radiates the energy at longer wavelengths to emit visible light. The blend of phosphors controls the color of the light, and along with the bulb's glass prevents the harmful UV light from escaping.

Only a fraction of the electrical energy input into a lamp gets turned into useful light. The ballast dissipates some heat; electronic ballasts may be around 90% efficient. A fixed voltage drop occurs at the electrodes. Some of the energy in the mercury vapor column is also dissipated, but about 85% is turned into visible and ultraviolet light.

Not all the UV energy on the phosphor gets converted into visible light. In a modern lamp, for every 100 incident photons of UV impacting the phosphor, only 86 visible light photons are emitted (a quantum efficiency of 86%). The largest single loss in modern lamps is due to the lower energy of each photon of visible light, compared to the energy of the UV photons that generated them. Incident photons have an energy of 5.5 electron volts but produce visible light photons with energy around 2.5 electron volts, so only 45% of the UV energy is used. If a so-called "two-photon" phosphor could be developed, this would improve the efficiency but much research has not yet found such a system.

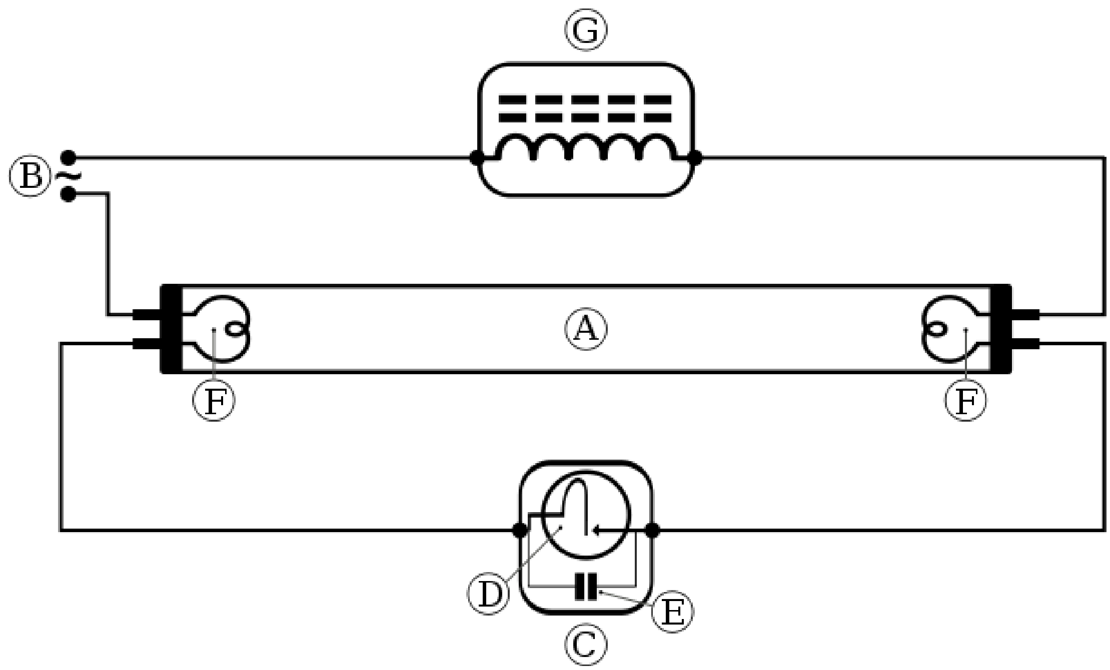
Cold cathode lamps

Most fluorescent lamps use electrodes that operate in thermionic emission mode, meaning they are operated at a high enough temperature for the chosen material (normally a special coating) to liberate electrons across to the gas-fill by heat.

However, there are also tubes that operate in cold cathode mode, whereby electrons are liberated only by the level of potential difference provided. This doesn't mean the electrodes are cold (and indeed, they can be very hot), but it does mean they are operating below their thermionic emission temperature. Because cold cathode lamps have no thermionic emission coating to wear out they can have much longer lives than is commonly available with thermionic emission tubes. This quality makes them desirable for maintenance-free long-life applications (such as LCD backlight displays). Sputtering of the electrode may still occur, but electrodes can be shaped (e.g. into an internal cylinder) to capture most of the sputtered material so it isn't lost from the electrode.

Cold cathode lamps are generally less efficient than thermionic emission lamps because the cathode fall voltage is much higher. The increased fall voltage results in more power dissipation at tube ends, which doesn't contribute to light output. However, this is less significant with longer tubes. The increased power dissipation at tube ends also usually means cold cathode tubes have to be run at a lower loading than their thermionic emission equivalents. Given the higher tube voltage required anyway, these tubes can easily be made long, and even run as series strings. They are better suited for bending into special shapes for lettering and signage, and can also be instantly switched on or off.

Starting



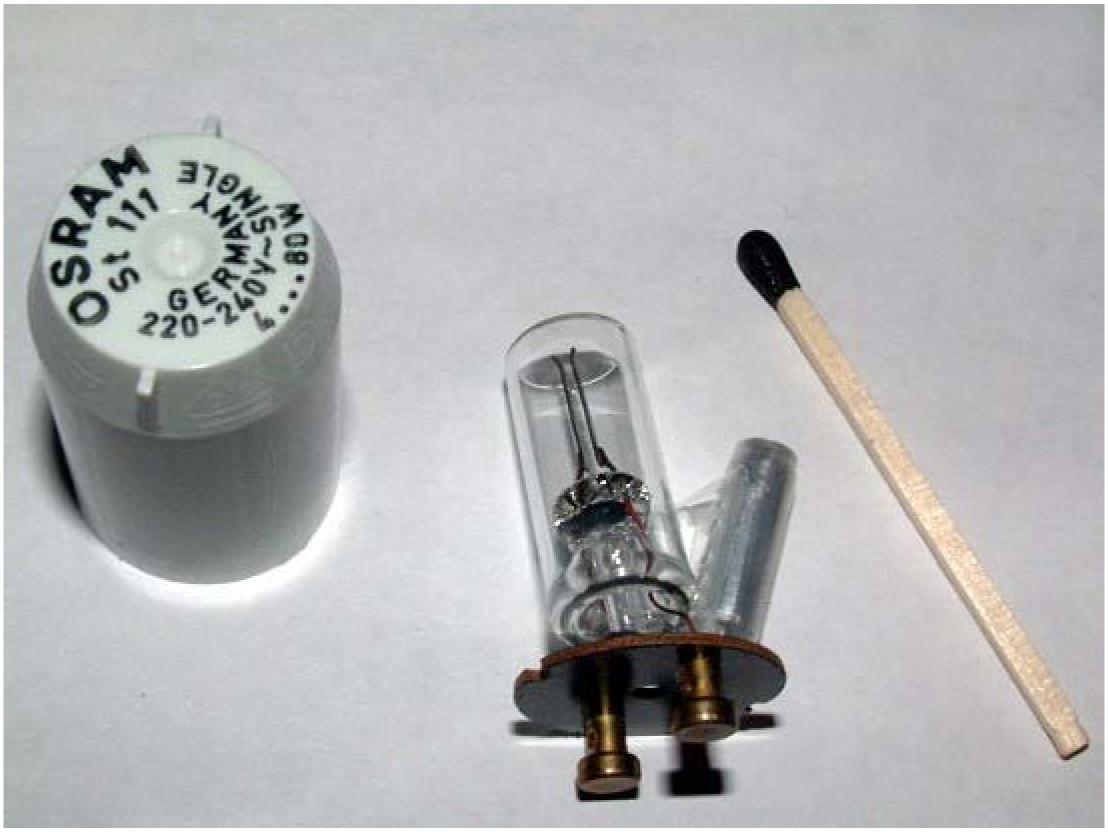
A *preheat* fluorescent lamp circuit using an automatic starting switch. A: Fluorescent tube, B: Power (+220 volts), C: Starter, D: Switch (bi-metallic thermostat), E: Capacitor, F: Filaments, G: Ballast

The mercury atoms in the fluorescent tube must be ionized before the arc can "strike" within the tube. For small lamps, it does not take much voltage to strike the arc and starting the lamp presents no problem, but larger tubes require a substantial voltage (in the range of a thousand volts).

Switchstart/preheat

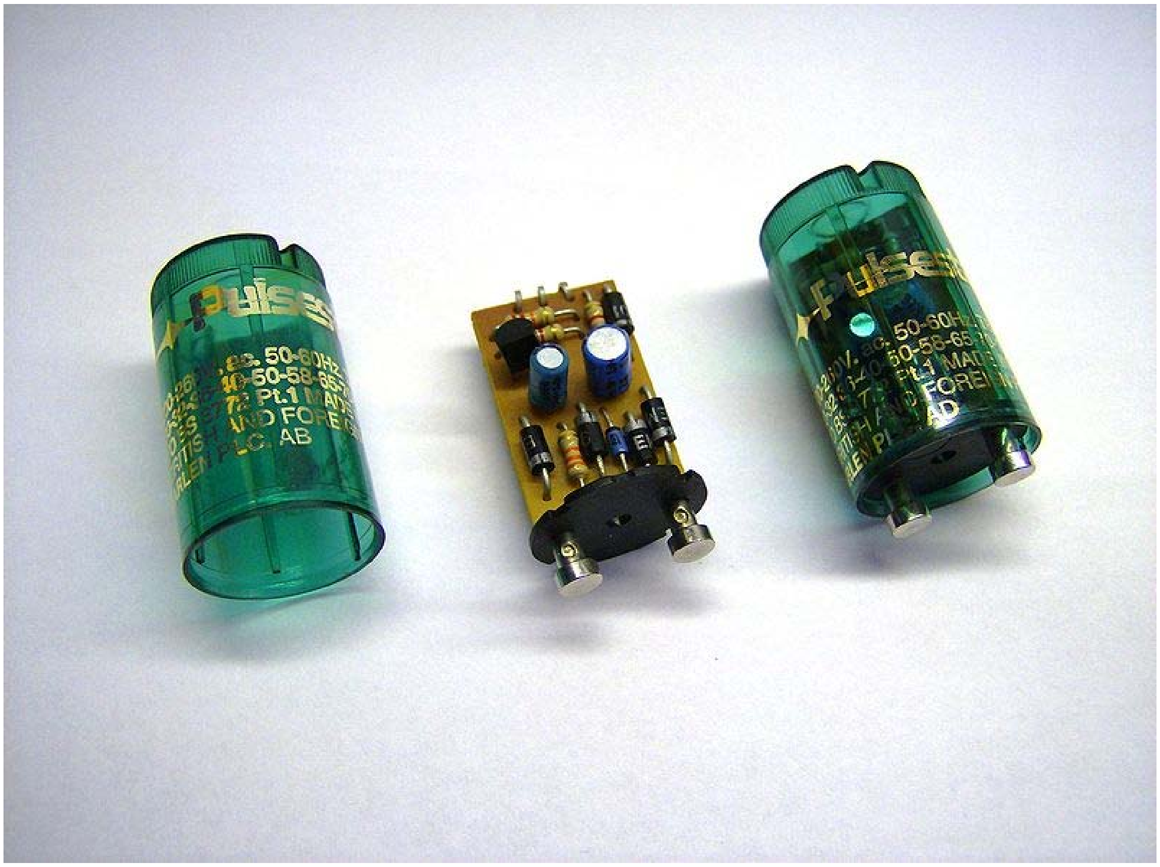
This technique uses a combination filament/cathode at each end of the lamp in conjunction with a mechanical or automatic switch that initially connect the filaments in series with the ballast and thereby preheat the filaments prior to striking the arc. Note that in North America, this is referred to as *Preheat*. Elsewhere this is referred to as *Switchstart*.

These systems are standard equipment in 200–240 V countries (and for 100–120 V lamps up to about 30 watts), and generally use a glow starter. Before the 1960s, four-pin thermal starters and manual switches were also used. Electronic starters are also sometimes used with these electromagnetic ballast lamp fittings.



A *preheat* fluorescent lamp "starter" (automatic starting switch)

The automatic glow starter shown in the photograph to the left consists of a small gas-discharge tube, containing neon and/or argon and fitted with a bi-metallic electrode. The special bi-metallic electrode is the key to the automatic starting mechanism.



Electronic fluorescent lamp starters

When power is first applied to the lamp circuit, a glow discharge will appear over the electrodes of the starter. This glow discharge will heat the gas in the starter and cause the bi-metallic electrode to bend towards the other electrode. When the electrodes touch, the two filaments of the fluorescent lamp and the ballast will effectively be switched in series to the supply voltage. This causes the filaments to glow and emit electrons into the gas column by thermionic emission. In the starter's tube, the touching electrodes have stopped the glow discharge, causing the gas to cool down again. The bi-metallic electrode also cools down and starts to move back. When the electrodes separate, the inductive kick from the ballast provides the high voltage to start the lamp. The starter additionally has a capacitor wired in parallel to its gas-discharge tube, in order to prolong the electrode life.

Once the tube is struck, the impinging main discharge then keeps the cathode hot, permitting continued emission without the need for the starter to close. The starter does not close again because the voltage across the lit tube is insufficient to start a glow discharge in the starter.

Tube strike is reliable in these systems, but glow starters will often cycle a few times before allowing the tube to stay lit, which causes undesirable flashing during starting. (The older thermal starters behaved better in this respect.)

If the tube fails to strike, or strikes but then extinguishes, the starting sequence is repeated. With automated starters such as glow starters, a failing tube will cycle endlessly, flashing as the lamp quickly goes out because emission is insufficient to keep the lamp current high enough to keep the glow starter open. This causes flickering, and runs the ballast at above design temperature. Some more advanced starters time out in this situation, and do not attempt repeated starts until power is reset. Some older systems used a thermal over-current trip to detect repeated starting attempts. These require manual reset.

Electronic starters use a more complex method to preheat the cathodes of a fluorescent lamp. They commonly use a specially designed semiconductor switch. They are programmed with a predefined preheat time to ensure that the cathodes are fully heated and reduce the amount of sputtered emission mix to prolong the life of the lamp. Electronic starters contain a series of capacitors that are capable of producing a high voltage pulse of electricity across the lamp to ensure that it strikes correctly. Electronic starters only attempt to start a lamp for a short time when power is initially applied and will not repeatedly attempt to restrike a lamp that is dead and cannot sustain an arc. This eliminates the re-striking of a lamp and the cycle of flashing that a failing lamp installed with a glow starter can produce. Electronic starters have also been developed that are capable of striking the fluorescent tube within 0.3 seconds, which gives a virtually instant start.

Instant start

In some cases, a high voltage is applied directly: *instant start* fluorescent tubes simply use a high enough voltage to break down the gas and mercury column and thereby start arc conduction. These tubes can be identified by a single pin at each end of the tube. The lamp holders have a "disconnect" socket at the low-voltage end to isolate the ballast and prevent electric shock. Low-cost lighting fixtures with an integrated electronic ballast use instant start on preheat lamps, even if it reduces the lamp lifespan.

Rapid start

Newer *rapid start* ballast designs provide filament power windings within the ballast; these rapidly and continuously warm the filaments/cathodes using low-voltage AC. No inductive voltage spike is produced for starting, so the lamps must be mounted near a grounded (earthed) reflector to allow the glow discharge to propagate through the tube and initiate the arc discharge. In some lamps a "starting aid" strip of grounded metal is attached to the outside of the lamp glass.

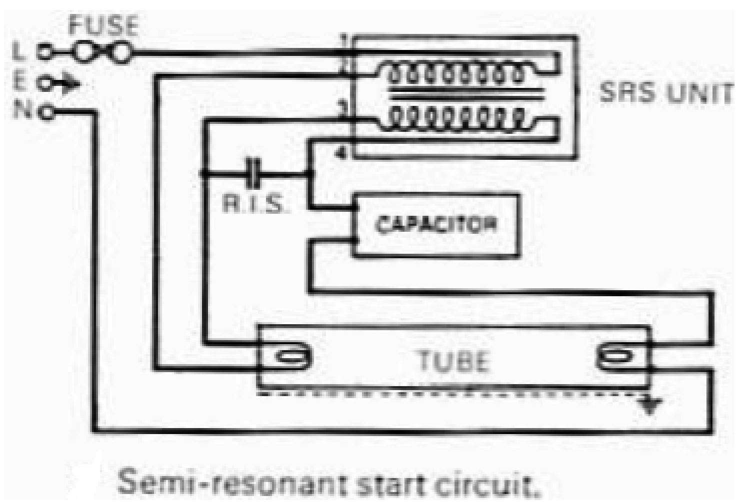
A rapid-start "iron" (magnetic) ballast continually heats the cathodes at the ends of the lamps. This ballast runs two F40T12 lamps in series.

Quick-start

Quick-start ballasts use a small auto-transformer to heat the filaments when power is first applied. When an arc strikes, the filament heating power is reduced and the tube will start within half a second. The auto-transformer is either combined with the ballast or may be a separate unit. Tubes need to be mounted near an earthed metal reflector in order for them to strike. Quick-start ballasts were more common in commercial installations because of lower maintenance as no starter switches need to be replaced. They are also used in domestic installations due to the virtually instant start. Quick-start ballasts are only used on 240 V circuits and are designed for use with the older, less-efficient T12 tubes, T8 retrofits will not start when used with quick-start ballasts.

Semi-resonant start

A 65 W semi-resonant lamp starting



A circuit diagram of a semi-resonant start fluorescent lamp

Semi-resonant start was invented by Thorn Lighting for use with T12 fluorescent tubes. This method uses a double wound transformer and a capacitor. With no arc current, the transformer and capacitor ring at mains frequency and generate about twice mains voltage across the tube, and a small electrode heating current. This tube voltage is too low to strike the arc with cold electrodes, but as the electrodes heat up to thermionic emission temperature, the tube striking voltage reduces below that of the ringing voltage, and the arc strikes. As the electrodes heat, the lamp slowly, over 3-5 seconds, reaches full brightness. As the arc current increases and tube voltage drops, the circuit provides current limiting.

Semi-resonant start was mainly used in commercial installations because of their higher initial cost. There are no starter switches to be replaced and cathode damage is reduced during starting. Due to the high open circuit tube voltage, this starting method was particularly good for starting tubes in cold locations. Additionally, the circuit power factor is almost 1.0, and no additional power factor correction is needed in the lighting installation. As the design requires that twice the mains voltage must be lower than the cold-cathode striking voltage (or the tubes would erroneously instant-start), this design can only be used with 5 ft and longer tubes on 240 V mains. Semi-resonant start fixtures are generally incompatible with energy saving T8 retrofit tubes, because such tubes have a higher starting voltage than T12 lamps and may not start reliably,especially in low temperatures. Recent proposals in some countries to phase out T12 tubes will reduce the application of this starting method.

Electronic ballasts

Electronic ballast for fluorescent lamp, 2x58W

Electronic ballasts and different compact fluorescent lamps

Starting a lamp that has an electronic ballast.

Electronic ballasts employ transistors to alter mains voltage frequency into high-frequency AC while also regulating the current flow in the lamp. These ballasts take advantage of the higher efficacy of lamps operated with higher-frequency current. Efficacy of a fluorescent lamp rises by almost 10% at a frequency of 10 kHz, compared to efficacy at normal power frequency. When the AC period is shorter than the relaxation time to de-ionize mercury atoms in the discharge column, the discharge stays closer to optimum operating condition. Electronic ballasts typically work in rapid start or instant start mode. Electronic ballasts are commonly supplied with AC power, which is internally converted to DC and then back to a variable frequency AC waveform. Depending upon the capacitance and the quality of constant-current pulse-width-modulation, this can largely eliminate modulation at 100 or 120 Hz.

Low cost ballasts mostly contain only a simple oscillator and series resonant LC circuit. When turned on, the oscillator starts, and the LC circuit charges. After a short time the voltage across the lamp reaches about 1 kV and the lamp ignites. The process is too fast to preheat the cathodes, so the lamp instant-starts in cold cathode mode. The cathode filaments are still used for protection of the ballast from overheating if the lamp does not ignite. A few manufacturers use positive temperature coefficient (PTC) thermistors to disable instant starting and give some time to preheat the filaments.

More complex electronic ballasts use programmed start. The output AC frequency is started above the resonance frequency of the output circuit of the ballast; and after the filaments are heated, the frequency is rapidly decreased. If the frequency approaches the resonant frequency of the ballast, the output voltage will increase so much that the lamp will ignite. If the lamp does not ignite, an electronic circuit stops the operation of the ballast.

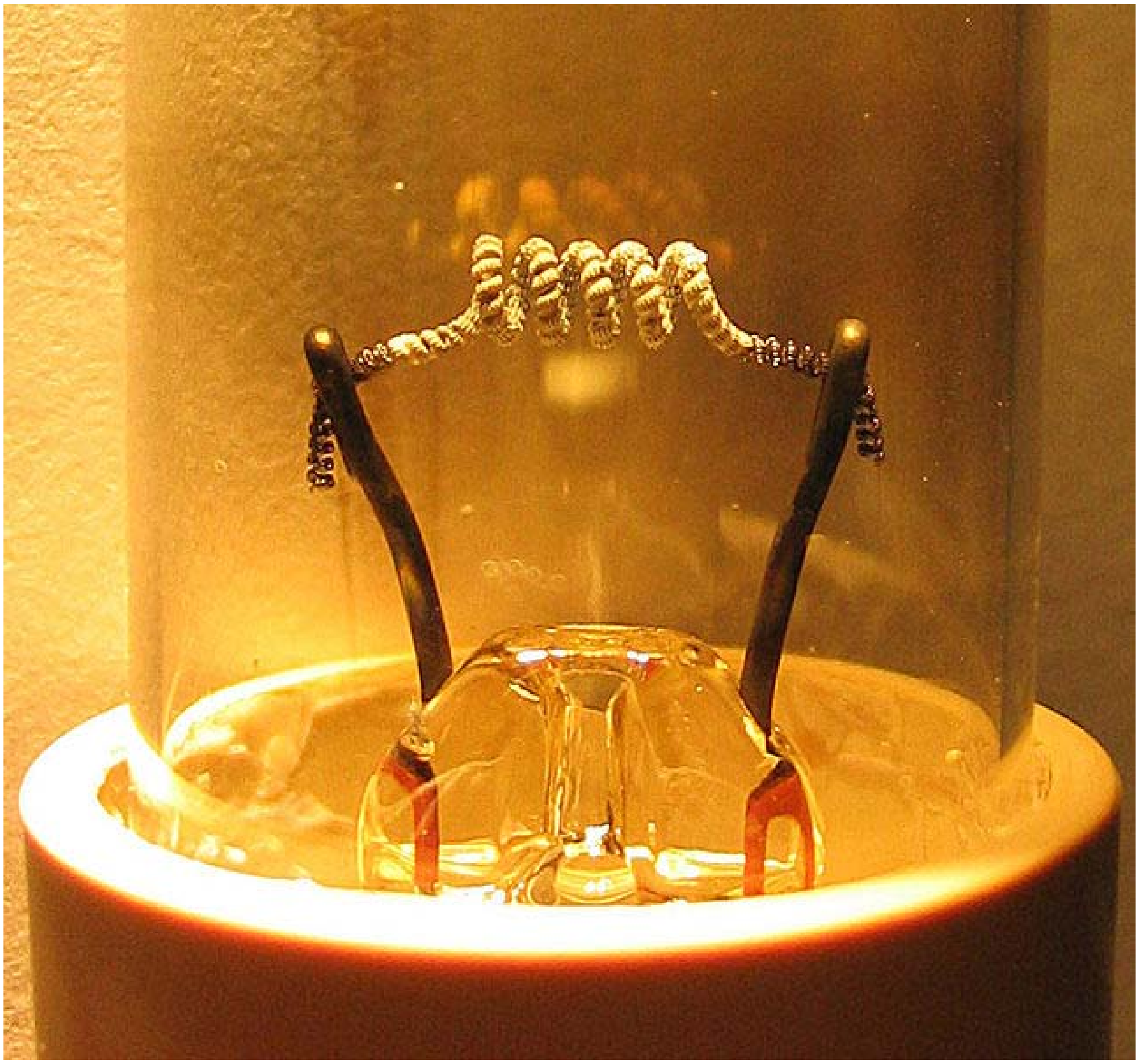
Many electronic ballasts are controlled by a microcontroller or similar, and these are sometimes called digital ballasts. Digital ballasts can apply quite complex logic to lamp starting and operation. This enables functions such as testing for broken electrodes and missing tubes before attempting to start, auto detect tube replacement, and auto detection of tube type, such that a single ballast can be used with several different tubes, even those that operate at different arc currents, etc. Once such fine grained control over the starting and arc current is achievable, features such as dimming, and having the ballast maintain a constant light level against changing sunlight contribution are all easily included in the embedded microcontroller software, and can be found in various manufacturers' products.

Since introduction in the 1990s, high frequency ballasts have been used in general lighting fixtures with either rapid start or pre-heat lamps. These ballasts convert the incoming power to an output frequency in excess of 20 kHz. This increases lamp efficiency. These are used in several applications, including new generation tanning lamp systems, whereby a 100 watt lamp (e.g., F71T12BP) can be lit using 65 to 70 watts of actual power while obtaining the same luminous flux (measured in lumens) as magnetic ballasts. These ballasts operate with voltages that can be almost 600 volts, requiring some consideration in housing design, and can cause a minor limitation in the length of the wire leads from the ballast to the lamp ends.

End of life

The end of life failure mode for fluorescent lamps varies depending how they are used and their control gear type. Normal tube failure modes are as follows:

Emission mix



Closeup of the filament on a low pressure mercury gas discharge lamp showing white thermionic emission mix coating on the central portion of the coil acting as hot cathode. Typically made of a mixture of barium, strontium and calcium oxides, the coating is sputtered away through normal use, often eventually resulting in lamp failure.

The "emission mix" on the tube filaments/cathodes is necessary to enable electrons to pass into the gas via thermionic emission at the tube operating voltages used. The mix is slowly sputtered off by bombardment with electrons and mercury ions during operation, but a larger amount is sputtered off each time the tube is started with cold cathodes. The method of starting the lamp has a significant impact on this. Lamps operated for typically less than 3 hours each switch-on will normally run out of the emission mix before other parts of the lamp fail. The sputtered emission mix forms the dark marks at the tube ends seen in old tubes. When all the emission mix is gone, the cathode cannot pass sufficient electrons into the gas fill to maintain the discharge at the designed tube operating voltage.

Ideally, the control gear should shut down the tube when this happens. However, some control gear will provide sufficient increased voltage to continue operating the tube in cold cathode mode, which will cause overheating of the tube end and rapid disintegration of the electrodes (filament goes open-circuit) and filament support wires until they are completely gone or the glass cracks, wrecking the low pressure gas fill and stopping the gas discharge.

Ballast electronics

This may occur in compact fluorescent lamps with integral electrical ballasts or in linear lamps. Ballast electronics failure is a somewhat random process that follows the standard failure profile for any electronic device. There is an initial small peak of early failures, followed by a drop and steady increase over lamp life. Life of electronics is heavily dependent on operating temperature—it typically halves for each 10 °C temperature rise. The quoted average life of a lamp is usually at 25 °C ambient (this may vary by country). The average life of the electronics at this temperature is normally greater than this, so at this temperature, not many lamps will fail due to failure of the electronics. In some fittings, the ambient temperature could be well above this, in which case failure of the electronics may become the predominant failure mechanism. Similarly, running a compact fluorescent lamp base-up will result in hotter electronics, which can cause shorter average life (particularly with higher power rated ones). Electronic ballasts should be designed to shut down the tube when the emission mix runs out as described above. In the case of integral electronic ballasts, since they never have to work again, this is sometimes done by having them deliberately burn out some component to permanently cease operation.

In most CFLs the filaments are connected in series, with a small capacitor between them. The discharge, once lit, is in parallel to the capacitor and presents a lower-resistance path, effectively shorting the capacitor out. One of the most common failure modes of cheap lamps is caused by underrating this capacitor (using lower-voltage, lower-cost part), which is very stressed during operation, leading to its premature failure.

Phosphor

The phosphor drops off in efficiency during use. By around 25,000 operating hours, it will typically be half the brightness of a new lamp (although some manufacturers claim much longer half-lives for their lamps). Lamps that do not suffer failures of the emission mix or integral ballast electronics will eventually develop this failure mode. They still work, but have become dim and inefficient. The process is slow, and often only becomes obvious when a new lamp is operating next to an old one.

Loss of mercury

Like in all mercury-based gas-filled tubes, mercury is slowly absorbed into glass, phosphor, and tube electrodes throughout the lamp life, where it can no longer function. Newer lamps now have just enough mercury to last the expected life of the lamp. Loss of mercury will take over from failure of the phosphor in some lamps. The failure symptoms are similar, except loss of mercury initially causes an extended run-up time to full light output, and finally causes the lamp to glow a dim pink when the mercury runs out and the argon base gas takes over as the primary discharge.

Subjecting the tube to asymmetric waveforms, where the total current flow through the tube does not cancel out and the tube effectively operates under a DC bias, causes asymmetric distribution of mercury ions along the tube due to cataphoresis. The localized depletion of mercury vapor pressure manifests as pink luminescence of the base gas in the vicinity of one of the electrodes, and the operating lifetime of the lamp may be dramatically shortened. This can be an issue with some poorly designed inverters.

The same effect can be observed with new tubes. Mercury is present in the form of an amalgam and takes some time to be liberated in sufficient amount. New lamps may initially glow pink for several seconds after startup. This period is minimized after about 100 hours of operation.

Burned filaments

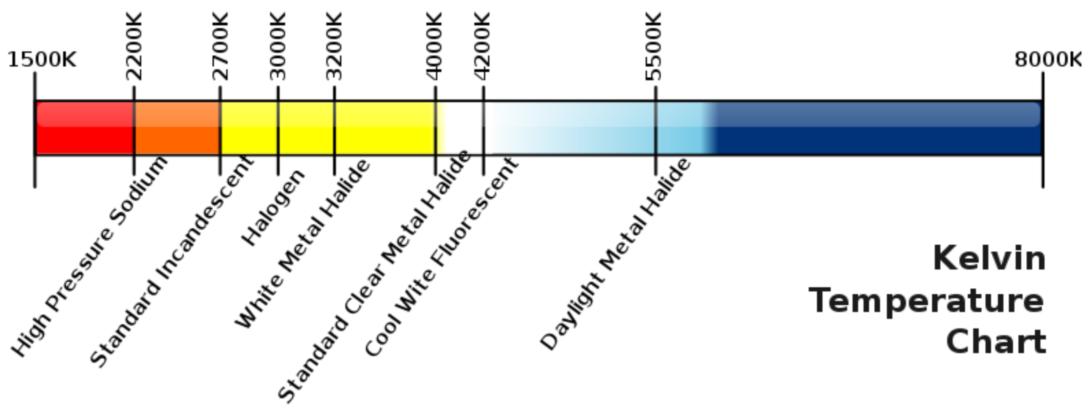
The filaments can burn at the end of the lamp's lifetime, opening the circuit and losing the capability to heat up. Both filaments lose function as they are connected in series, with just a simple switch start circuit a broken filament will render the lamp completely useless. Filaments rarely burn or fail open circuit unless the filament becomes depleted of emitter and the control gear is able to supply a high enough voltage across the tube to operate it in cold cathode mode. Some digital electronic ballasts are capable of detecting broken filaments and can still strike an arc with one or both filaments broken providing there is still sufficient emitter. A broken filament in a bulb attached to a magnetic ballast often causes both bulbs to burn out or flicker.

Phosphors and the spectrum of emitted light

Light from a fluorescent tube lamp reflected by a CD shows the individual bands of color.

The spectrum of light emitted from a fluorescent lamp is the combination of light directly emitted by the mercury vapor, and light emitted by the phosphorescent coating. The spectral lines from the mercury emission and the phosphorescence effect give a combined spectral distribution of light that is different from those produced by incandescent sources. The relative intensity of light emitted in each narrow band of wavelengths over the visible spectrum is in different proportions compared to that of an incandescent source. Colored objects are perceived differently under light sources with differing spectral distributions. For example, some people find the color rendition produced by some fluorescent lamps to be harsh and displeasing. A healthy person can sometimes appear to have an unhealthy skin tone under fluorescent lighting. The extent to which this phenomenon occurs is related to the light's spectral composition, and may be gauged by its color rendering index (CRI).

Color temperature



The color temperature of different electric lamps

Correlated color temperature (CCT) is a measure of the "shade" of whiteness of a light source, again by comparison with a blackbody. Typical incandescent lighting is 2700 K, which is yellowish-white. Halogen lighting is 3000 K. Fluorescent lamps are manufactured to a chosen CCT by altering the mixture of phosphors inside the tube. Warm-white fluorescents have CCT of 2700 K and are popular for residential lighting. Neutral-white fluorescents have a CCT of 3000 K or 3500 K. Cool-white fluorescents have a CCT of 4100 K and are popular for office lighting. Daylight fluorescents have a CCT of 5000 K to 6500 K, which is bluish-white.

High CCT lighting generally requires higher light levels. At dimmer illumination levels, the human eye perceives lower color temperatures as more natural, as related through the Kruithof curve. So, a dim 2700 K incandescent lamp appears natural and a bright 5000 K lamp also appears natural, but a dim 5000 K fluorescent lamp appears too pale. Daylight-type fluorescents look natural only if they are very bright.

Color rendering index

Color rendering index (CRI) is a measure of how well colors can be perceived using light from a source, relative to light from a reference source such as daylight or a blackbody of the same color temperature. By definition, an incandescent lamp has a CRI of 100. Real-life fluorescent tubes achieve CRIs of anywhere from 50 to 99. Fluorescent lamps with low CRI have phosphors that emit too little red light. Skin appears less pink, and hence "unhealthy" compared with incandescent lighting. Colored objects appear muted. For example, a low CRI 6800 K halophosphate tube (an extreme example) will make reds appear dull red or even brown. Since the eye is relatively less efficient at detecting red light, an improvement in color rendering index, with increased energy in the red part of the spectrum, may reduce the overall luminous efficacy.

Lighting arrangements use fluorescent tubes in an assortment of tints of white. Sometimes this is because of the lack of appreciation for the difference or importance of differing tube types. Mixing tube types within fittings can improve the color reproduction of lower quality tubes.

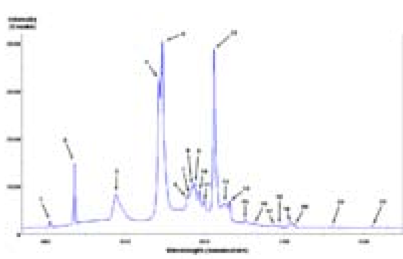
Phosphor composition

Some of the least pleasant light comes from tubes containing the older, halophosphate-type phosphors (chemical formula $Ca_5(PO_4)_3(F, Cl):Sb^{3+}, Mn^{2+}$). This phosphor mainly emits yellow and blue light, and relatively little green and red. In the absence of a reference, this mixture appears white to the eye, but the light has an incomplete spectrum. The CRI of such lamps is around 60.

Since the 1990s, higher quality fluorescent lamps use either a higher CRI halophosphate coating, or a *triphosphor* mixture, based on europium and terbium ions, that have emission bands more evenly distributed over the spectrum of visible light. High CRI halophosphate and triphosphor tubes give a more natural color reproduction to the human eye. The CRI of such lamps is typically 82–100.

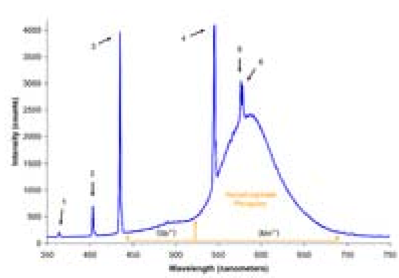
Fluorescent lamp spectra

Typical fluorescent lamp with "rare earth" phosphor



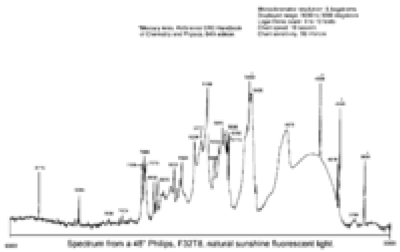
A typical "cool white" fluorescent lamp utilizing two rare earth doped phosphors, $Tb^{3+}, Ce^{3+}:LaPO_4$ for green and blue emission and $Eu:Y_2O_3$ for red. Note that several of the spectral peaks are directly generated from the mercury arc. This is likely the most common type of fluorescent lamp in use today.

An older style halophosphate phosphor fluorescent lamp



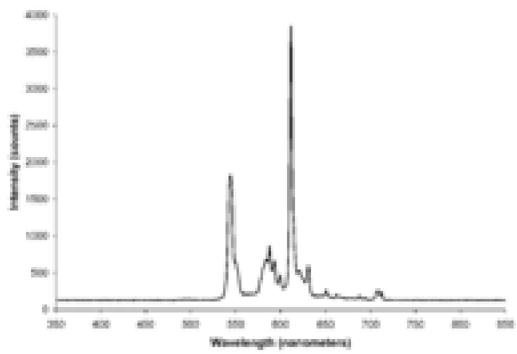
Halophosphate phosphors in these lamps usually consist of trivalent antimony and divalent manganese doped calcium halophosphate ($Ca_5(PO_4)_3(Cl, F):Sb^{3+}, Mn^{2+}$). The color of the light output can be adjusted by altering the ratio of the blue emitting antimony dopant and orange emitting manganese dopant. The color rendering ability of these older style lamps is quite poor. Halophosphate phosphors were invented by A.H. McKeag *et al.* in 1942.

"Natural sunshine" fluorescent light



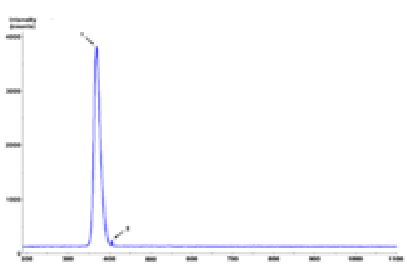
An explanation of the origin of the peaks is on the image page.

Yellow fluorescent lights



The spectrum is nearly identical to a normal fluorescent bulb except for a near total lack of light below 500 nanometers. This effect can be achieved through either specialized phosphor use or more commonly by the use of a simple yellow light filter. These lamps are commonly used as lighting for photolithography work in cleanrooms and as "bug repellent" outdoor lighting (the efficacy of which is questionable).

Spectrum of a "blacklight" bulb



There is typically only one phosphor present in a blacklight bulb, usually consisting of europium-doped strontium fluoroborate, which is contained in an envelope of Wood's glass.

Applications

Fluorescent light bulbs come in many shapes and sizes. The compact fluorescent light bulb (CFL) is becoming more popular. Many compact fluorescent lamps integrate the auxiliary electronics into the base of the lamp, allowing them to fit into a regular light bulb socket.

In US residences, fluorescent lamps are mostly found in kitchens, basements, or garages, but schools and businesses find the cost savings of fluorescent lamps to be significant and rarely use incandescent lights. Tax incentives and environmental awareness result in higher use in places such as California.

In other countries, residential use of fluorescent lighting varies depending on the price of energy, financial and environmental concerns of the local population, and acceptability of the light output. In East and Southeast Asia it is very rare to see incandescent bulbs in buildings anywhere.

Some countries are encouraging the phase-out of incandescent light bulbs and substitution of incandescent lamps with fluorescent lamps or other types of energy-efficient lamps.

The newest fluorescent lamps can be used to grow indoor plants to maturity. These lamps are marketed as High-Output T5 Fluorescents. The T8 and T12 predecessors can be used to rear seedlings, but are not powerful enough for mature plant growth.

In addition to general lighting, special fluorescent lights are often used in stage lighting for film and video production. They are cooler than traditional halogen light sources, and use high-frequency ballasts to prevent video flickering and high color-rendition index bulbs to approximate daylight color temperatures.

Advantages

Luminous efficacy

Fluorescent lamps convert more of the input power to visible light than incandescent lamps. A typical 100 watt tungsten filament incandescent lamp may convert only 2% of its power input to visible white light, whereas typical fluorescent lamps convert about 22% of the power input to visible white light.

The efficacy of fluorescent tubes ranges from about 16 lumens per watt for a 4 watt tube with an ordinary ballast to over 100 lumens per watt with a modern electronic ballast, commonly averaging 50 to 67 lm/W overall. Most compact fluorescents above 13 watts with integral electronic ballasts achieve about 60 lm/W. Lamps are rated by lumens after 100 hours of operation. For a given fluorescent tube, a high-frequency electronic ballast gives about a 10% efficacy improvement over an inductive ballast. It is necessary to include the ballast loss when evaluating the efficacy of a fluorescent lamp system; this can be about 25% of the lamp power with magnetic ballasts, and around 10% with electronic ballasts.

Fluorescent lamp efficacy is dependent on lamp temperature at the coldest part of the lamp. In T8 lamps this is in the center of the tube. In T5 lamps this is at the end of the tube with the text stamped on it. The ideal temperature for a T8 lamp is 25 °C (77 °F) while the T5 lamp is ideally at 35 °C (95 °F).

Life

Typically a fluorescent lamp will last between 10 to 20 times as long as an equivalent incandescent lamp when operated several hours at a time.

The higher initial cost of a fluorescent lamp is usually more than compensated for by lower energy consumption over its life. The longer life may also reduce lamp replacement costs, providing additional saving especially where labour is costly. Therefore they are widely used by businesses and institutions, but not as much by households.

Lower luminosity

Compared with an incandescent lamp, a fluorescent tube is a more diffuse and physically larger light source. In suitably designed lamps, light can be more evenly distributed without point source of glare such as seen from an undiffused incandescent filament; the lamp is large compared to the typical distance between lamp and illuminated surfaces.

Lower heat

About two-thirds to three-quarters less heat is given off by fluorescent lamps compared to an equivalent installation of incandescent lamps. This greatly reduces the size, cost, and energy consumption.

Disadvantages

Frequent switching

If the lamp is installed where it is frequently switched on and off, it will age rapidly. Under extreme conditions, its lifespan may be much shorter than a cheap incandescent lamp. Each start cycle slightly erodes the electron-emitting surface of the cathodes; when all the emission material is gone, the lamp cannot start with the available ballast voltage. Fixtures intended for flashing of lights (such as for advertising) will use a ballast that maintains cathode temperature when the arc is off, preserving the life of the lamp.

Health and safety issues

If a fluorescent lamp is broken, a very small amount of mercury can contaminate the surrounding environment. About 99% of the mercury is typically contained in the phosphor, especially on lamps that are near their end of life. The broken glass is usually considered a greater hazard than the small amount of spilled mercury. The EPA recommends airing out the location of a fluorescent tube break and using wet paper towels to help pick up the broken glass and fine particles. Any glass and used towels should be disposed of in a sealed plastic bag. Vacuum cleaners can cause the particles to become airborne, and should not be used.

Ultraviolet emission

Fluorescent lamps emit a small amount of ultraviolet (UV) light. A 1993 study in the US found that UV exposure from sitting under fluorescent lights for eight hours is equivalent to only one minute of sun exposure. Very sensitive individuals may experience a variety of health problems relating to light sensitivity that is aggravated by artificial lighting.

UV light can affect sensitive paintings, especially watercolors and many textiles. Valuable art work must be protected from light by additional glass or transparent acrylic sheets put between the lamp(s) and the painting.

Ballast

Magnetic single-lamp ballasts have a low power factor

Fluorescent lamps require a ballast to stabilize the current through the lamp, and to provide the initial striking voltage required to start the arc discharge. This increases the cost of fluorescent light fixtures, though often one ballast is shared between two or more lamps. Electromagnetic ballasts with a minor fault can produce an audible humming or buzzing noise. Magnetic ballasts are usually filled with a tar-like potting compound to reduce emitted noise. Hum is eliminated in lamps with a high-frequency electronic ballast. Energy lost in magnetic ballasts can be significant, on the order of 10% of lamp input power. Electronic ballasts reduce this loss.

Power quality and radio interference

Simple inductive fluorescent lamp ballasts have a power factor of less than unity. Inductive ballasts include power factor correction capacitors. Simple electronic ballasts may also have low power factor due to their rectifier input stage.

Fluorescent lamps are a non-linear load and generate harmonic currents in the electrical power supply. The arc within the lamp may generate radio frequency noise, which can be conducted through power wiring. Suppression of radio interference is possible. Very good suppression is possible, but adds to the cost of the fluorescent fixtures.

Operating temperature

Fluorescent lamps operate best around room temperature. At much lower or higher temperatures, efficiency decreases. At below-freezing temperatures standard lamps may not start. Special lamps may be needed for reliable service outdoors in cold weather. In applications such as road and railway signalling, fluorescent lamps which do not generate as much heat as incandescent lamps may not melt snow and ice build up around the lamp, leading to reduced visibility.

Lamp shape

Fluorescent tubes are long, low-luminance sources compared with high pressure arc lamps and incandescent lamps. However, low luminous intensity of the emitting surface is useful because it reduces glare. Lamp fixture design must control light from a long tube instead of a compact globe.

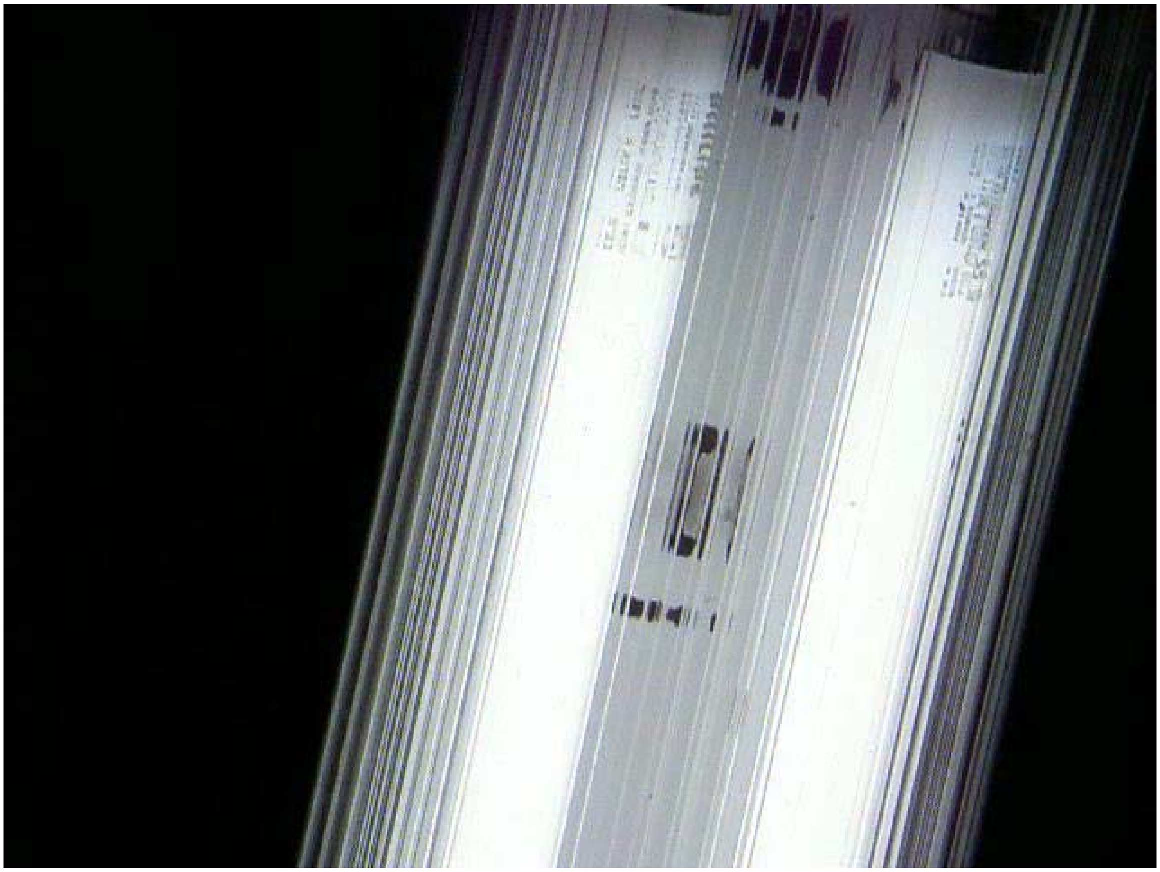
The compact fluorescent lamp (CFL) replaces regular incandescent bulbs. However, some CFLs will not fit some lamps, because the harp (heavy wire shade support bracket) is shaped for the narrow neck of an incandescent lamp, while CFLs tend to have a wide housing for their electronic ballast close to the bulb's base.

Flicker problems

The "beat effect" problem created when shooting photos under standard fluorescent lighting

Fluorescent lamps using a magnetic mains frequency ballast do not give out a steady light; instead, they flicker at twice the supply frequency. This results in fluctuations not only with light output but color temperature as well, which may pose problems for photography and people who are sensitive to the flicker. Even among persons not sensitive to light flicker, a stroboscopic effect can be noticed, where something spinning at just the right speed may appear stationary if illuminated solely by a single fluorescent lamp. This effect is eliminated by paired lamps operating on a lead-lag ballast. Unlike a true strobe lamp, the light level drops in appreciable time and so substantial "blurring" of the moving part would be evident.

In some circumstances, fluorescent lamps operated at mains frequency can also produce flicker at the mains frequency (50 or 60 Hz) itself, which is noticeable by more people. This can happen in the last few hours of tube life when the cathode emission coating at one end has almost run out, and that cathode starts having difficulty emitting enough electrons into the gas fill, resulting in slight rectification and hence uneven light output in positive and negative going mains cycles. Mains frequency flicker can also sometimes be emitted from the very ends of the tubes, if each tube electrode produces a slightly different light output pattern on each half-cycle. Flicker at mains frequency is more noticeable in the peripheral vision than it is when viewed directly.



The "beat effect" problem created when shooting films under standard fluorescent lighting at a low refresh rate.

New fluorescent lamps may show a twisting spiral pattern of light in a part of the lamp. This effect is due to loose cathode material and usually disappears after a few hours of operation.

Electromagnetic ballasts may also cause problems for video recording as there can be a "beat effect" between the periodic reading of a camera's sensor and the fluctuations in intensity of the fluorescent lamp.

Fluorescent lamps using high-frequency electronic ballasts do not produce visible light flicker, since above about 5 kHz, the excited electron state half-life is longer than a half cycle, and light production becomes continuous. Operating frequencies of electronic ballasts are selected to avoid interference with infrared remote controls. Poor quality (or failing) electronic ballasts may have insufficient reservoir capacitance or have poor regulation, thereby producing considerable 100/120 Hz modulation of the light.

Dimming

Fluorescent light fixtures cannot be connected to dimmer switches intended for incandescent lamps. Two effects are responsible for this: the waveform of the voltage emitted by a standard phase-control dimmer interacts badly with many ballasts, and it becomes difficult to sustain an arc in the fluorescent tube at low power levels. Dimming installations require a compatible dimming ballast. These systems keep the cathodes of the fluorescent tube fully heated even as the arc current is reduced, promoting easy thermionic emission of electrons into the arc stream. CFLs are available that work in conjunction with a suitable dimmer.

Disposal and recycling

The disposal of phosphor and particularly the toxic mercury in the tubes is an environmental issue. Governmental regulations in many areas require special disposal of fluorescent lamps separate from general and household wastes. For large commercial or industrial users of fluorescent lights, recycling services are available in many nations, and may be required by regulation. In some areas, recycling is also available to consumers.

Lamp sizes and designations

Systematic nomenclature identifies mass-market lamps as to general shape, power rating, length, color, and other electrical and illuminating characteristics.

Other fluorescent lamps

Black lights
: Blacklights are a subset of fluorescent lamps that are used to provide near ultraviolet light (at about 360 nm wavelength). They are built in the same fashion as conventional fluorescent lamps but the glass tube is coated with a phosphor that converts the short-wave UV within the tube to long-wave UV rather than to visible light. They are used to provoke fluorescence (to provide dramatic effects using blacklight paint and to detect materials such as urine and certain dyes that would be invisible in visible light) as well as to attract insects to bug zappers. So-called *blacklite blue* lamps are also made from more expensive deep purple glass known as Wood's glass rather than clear glass. The deep purple glass filters out most of the visible colors of light directly emitted by the mercury-vapor discharge, producing proportionally less visible light compared with UV light. This allows UV-induced fluorescence to be seen more easily (thereby allowing blacklight posters to seem much more dramatic). The blacklight lamps used in bug zappers do not require this refinement so it is usually omitted in the interest of cost; they are called simply *blacklite* (and not blacklite blue).

Tanning lamps
: The lamps used in tanning beds contain a different phosphor blend (typically 3 to 5 or more phosphors) that emits both UVA and UVB, provoking a tanning

response in most human skin. Typically, the output is rated as 3% to 10% UVB (5% most typical) with the remaining UV as UVA. These are mainly F71, F72 or F73 HO (100 W) lamps, although 160 W VHO are somewhat common. One common phosphor used in these lamps is lead-activated barium disilicate, but a europium-activated strontium fluoroborate is also used. Early lamps used thallium as an activator, but emissions of thallium during manufacture were toxic.

Grow lamps

Grow lamps contain phosphor blends that encourage photosynthesis, growth, and/or flowering in plants, algae, photosynthetic bacteria, and other light-dependent organisms. These often emit light in the red and blue color range, which is absorbed by chlorophyll and used for photosynthesis in plants.

Infrared lamps

Lamps can be made with a lithium metaluminate phosphor activated with iron. This phosphor has peak emissions between 675 and 875 nanometers, with lesser emissions in the deep red part of the visible spectrum.

Bilirubin lamps

Deep blue light generated from a europium-activated phosphor is used in the light therapy treatment of jaundice; light of this color penetrates skin and helps in the break up of excess bilirubin.

Germicidal lamps

Germicidal lamps depend on the property that UV light kills most germs. Germicidal lamps contain no phosphor at all (making them gas discharge lamps rather than fluorescent) and their tubes are made of fused quartz that is transparent to the UV light emitted by the mercury discharge. The UV emitted by these tubes will kill germs and ionize oxygen to ozone. In addition it can cause eye and skin damage and should not be used or observed without eye and skin protection. Besides their uses to kill germs and create ozone, they are sometimes used by geologists to identify certain species of minerals by the color of their fluorescence. When used in this fashion, they are fitted with filters in the same way as blacklight-blue lamps are; the filter passes the short-wave UV and blocks the visible light produced by the mercury discharge. They are also used in some EPROM erasers.

Germicidal lamps have designations beginning with G (meaning 'Germicidal'), rather than F, for example G30T8 for a 30-watt, 1-inch (2.5 cm) diameter, 36-inch (91 cm) long germicidal lamp (as opposed to an F30T8, which would be the fluorescent lamp of the same size and rating).

Electrodeless lamps

Electrodeless induction lamps are fluorescent lamps without internal electrodes. They have been commercially available since 1990. A current is induced into the gas column using electromagnetic induction. Because the electrodes are usually the life-limiting element of fluorescent lamps, such electrodeless lamps can have a very long service life, although they also have a higher purchase price.

Cold-cathode fluorescent lamps (CCFL)

Cold-cathode fluorescent lamps are used as backlighting for LCD displays in personal computer and TV monitors. They are also popular with computer case modders in recent years.

Science demonstrations

Capacitive coupling with high-voltage power lines can light a lamp continuously at low intensity

Fluorescent lamps can be illuminated by means other than a proper electrical connection. These other methods, however, result in very dim or very short-lived illumination, and so are seen mostly in science demonstrations. Static electricity or a Van de Graaff generator will cause a lamp to flash momentarily as it discharges a high voltage capacitance. A Tesla coil will pass high frequency current through the tube, and since it has a high voltage as well, the gases within the tube will ionize and emit light. Capacitive coupling with high-voltage power lines can light a lamp continuously at low intensity, depending on the intensity of the electrostatic field.

Also, placing a bulb half way up a two-way radio antenna while transmitting will illuminate the bulb due to the RF energy.

Chapter- 3

Compact Fluorescent Lamp

The tubular-type compact fluorescent lamp is one of the most popular types in Europe.

A spiral-type integrated CFL. This style has slightly reduced efficiency compared to tubular fluorescent lamps, due to the thicker layer of phosphor on the lower side of the twist. It has been the most popular type in North America since the mid 1990s, when the final expiration of patents allowed its manufacture.

A **compact fluorescent lamp** (**CFL**), also known as a **compact fluorescent light** or **energy saving light** (or less commonly as a **compact fluorescent tube**), is a type of fluorescent lamp. Many CFLs are designed to replace an incandescent lamp and can fit into most existing light fixtures formerly used for incandescents.

Compared to general service incandescent lamps giving the same amount of visible light, CFLs use less power and have a longer rated life. In the United States, a CFL has a higher purchase price than an incandescent lamp, but can save over US$40 in electricity costs over the lamp's lifetime. Like all fluorescent lamps, CFLs contain mercury, which complicates their disposal.

CFLs radiate a different light spectrum from that of incandescent lamps. Improved phosphor formulations have improved the perceived colour of the light emitted by CFLs such that some sources rate the best 'soft white' CFLs as subjectively similar in colour to standard incandescent lamps.

History

An early compact fluorescent lamp

The parent to the modern fluorescent lamp was invented in the late 1890s by Peter Cooper Hewitt. The Cooper Hewitt lamps were used for photographic studios and industries.

Edmund Germer, Friedrich Meyer, and Hans Spanner then patented a high pressure vapor lamp in 1927. George Inman later teamed with General Electric to create a practical fluorescent lamp, sold in 1938 and patented in 1941. Circular and U-shaped lamps were devised to reduce the length of fluorescent light fixtures. The first fluorescent bulb and fixture were displayed to the general public at the 1939 New York World's Fair.

The spiral tube CFL was invented in 1976 by Edward E. Hammer, an engineer with General Electric, in response to the 1973 oil crisis. The design met its goals, and it would have cost GE only about US$25 million to build new factories to produce them, but the invention was shelved. The design was eventually copied by others. It was not until 1995 that spiral lamps manufactured in China were commercially available; spiral lamps have steadily increased in sales volume.

In 1980, Philips introduced its model SL, which was a screw-in lamp with integral ballast. The lamp used a folded T4 tube, stable tri-color phosphors, and a mercury amalgam. This was the first successful screw-in replacement for an incandescent lamp. In 1985 Osram started selling their model EL lamp which was the first CFL to include an electronic ballast.

Development of fluorescent lamps that could fit in the same volume as comparable incandescent lamps required the development of new, high-efficacy phosphors that could withstand more power per unit area than the phosphors used in older, larger fluorescent tubes.

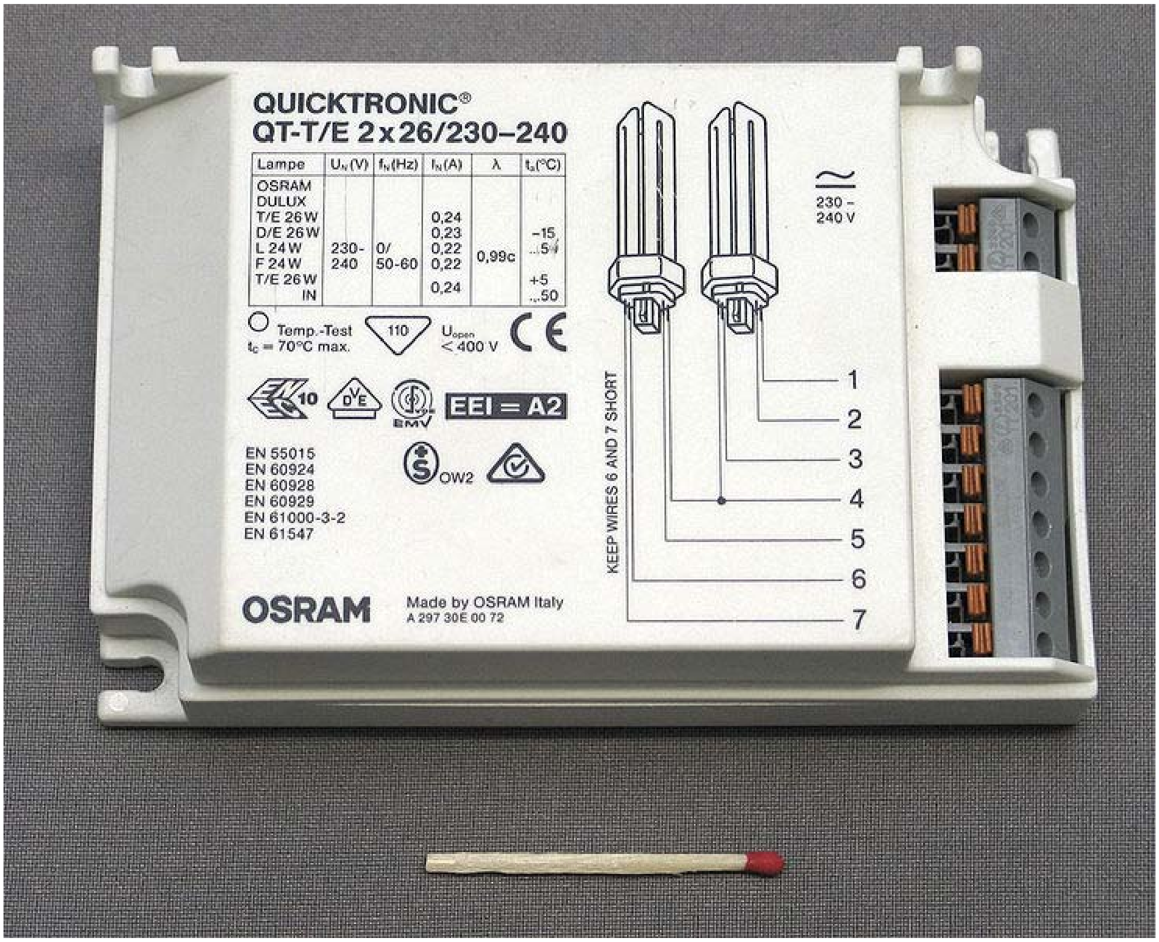
Construction

A compact fluorescent lamp used outside of a building.

The most important technical advance has been the replacement of electromagnetic ballasts with electronic ballasts; this has removed most of the flickering and slow starting traditionally associated with fluorescent lighting.

There are two types of CFLs: integrated and non-integrated lamps. Integrated lamps combine a tube, an electronic ballast and either an Edison screw or a bayonet fitting in a single unit. These lamps allow consumers to replace incandescent lamps easily with CFLs. Integrated CFLs work well in many standard incandescent light fixtures, reducing the cost of converting to fluorescent. Special 3-way models and dimmable models with standard bases are available.

Non-integrated bi-pin double-turn compact fluorescent lamp

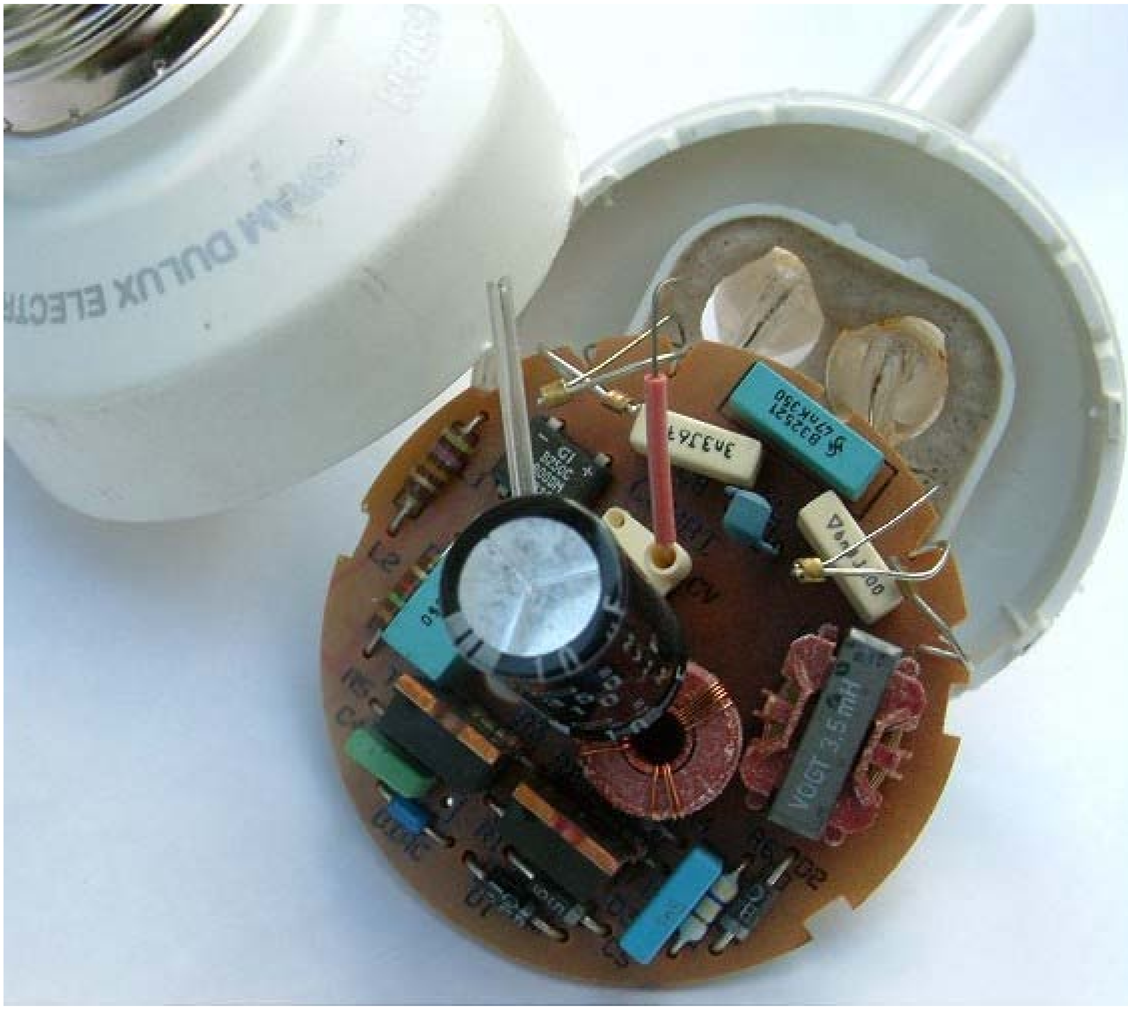


Non-integrated electronic ballast for compact fluorescent lamps

Non-integrated CFLs have the ballast permanently installed in the luminaire, and only the lamp bulb is usually changed at its end of life. Since the ballasts are placed in the light fixture they are larger and last longer compared to the integrated ones, and they don't need to be replaced when the bulb reaches its end-of-life. Non-integrated CFL housings can be both more expensive and sophisticated. They have two types of tubes: a bi-pin tube designed for a conventional ballast, and a quad-pin tube designed for an electronic ballast or a conventional ballast with an external starter. A bi-pin tube contains an integrated starter which obviates the need for external heating pins but causes incompatibility with electronic ballasts.

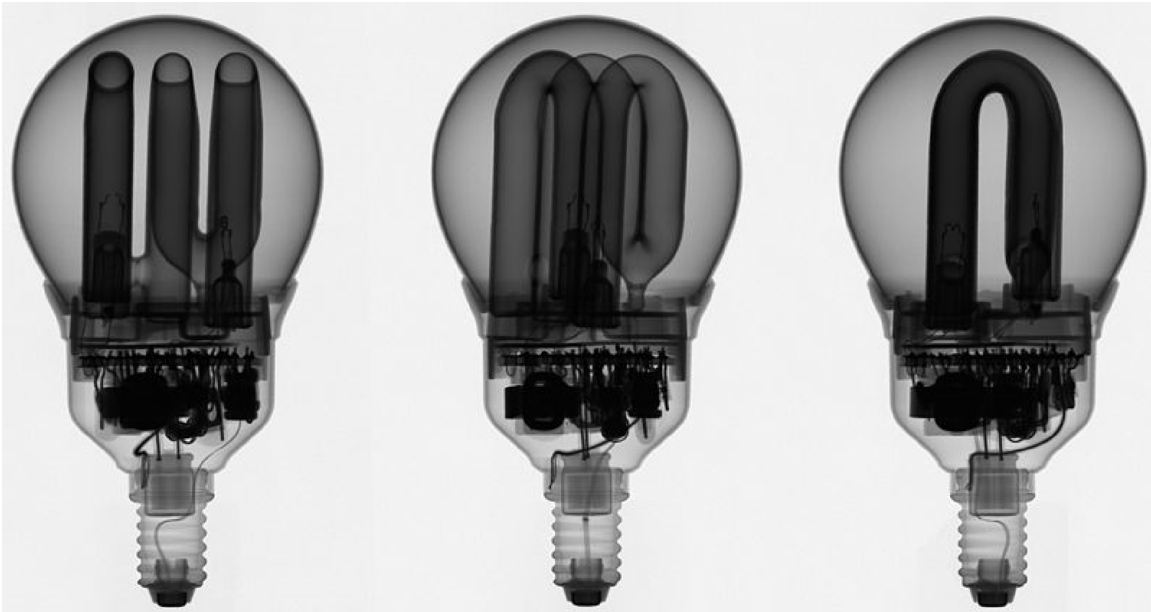
Components

CFLs have two main components: a gas-filled tube (also called bulb or burner) and a magnetic or electronic ballast.



An electronic ballast and permanently attached tube in an integrated CFL

Standard shapes of CFL tube are single-turn double helix, double-turn, triple-turn, quad-turn, circular, and butterfly.



Stitched X-ray image from three different angles (0°, 45°, 90°) of a defective IKEA compact fluorescent lamp. The burned through filament is visible in the left image.

Electronic ballasts contain a small circuit board with rectifiers, a filter capacitor and usually two switching transistors connected as a high-frequency resonant series DC to AC inverter. The resulting high frequency, around 40 kHz or higher, is applied to the lamp tube. Since the resonant converter tends to stabilize lamp current (and light produced) over a range of input voltages, standard CFLs do not respond well in dimming applications and special lamps are required for dimming service. CFLs that flicker when they start have magnetic ballasts; CFLs with electronic ballasts are now much more common.

CFL power sources

CFLs are produced for both alternating current (AC) and direct current (DC) input. DC CFLs are popular for use in recreational vehicles and off-the-grid housing. There are various aid agency led initiatives in developing countries to replace kerosene lanterns (with their associated health hazards) with DC CFLs (with car batteries and small solar panels or wind generators).

CFLs can also be operated with solar powered street lights, using solar panels located on the top or sides of a pole and light fixtures that are specially wired to use the lamps.

Comparison with incandescent lamps

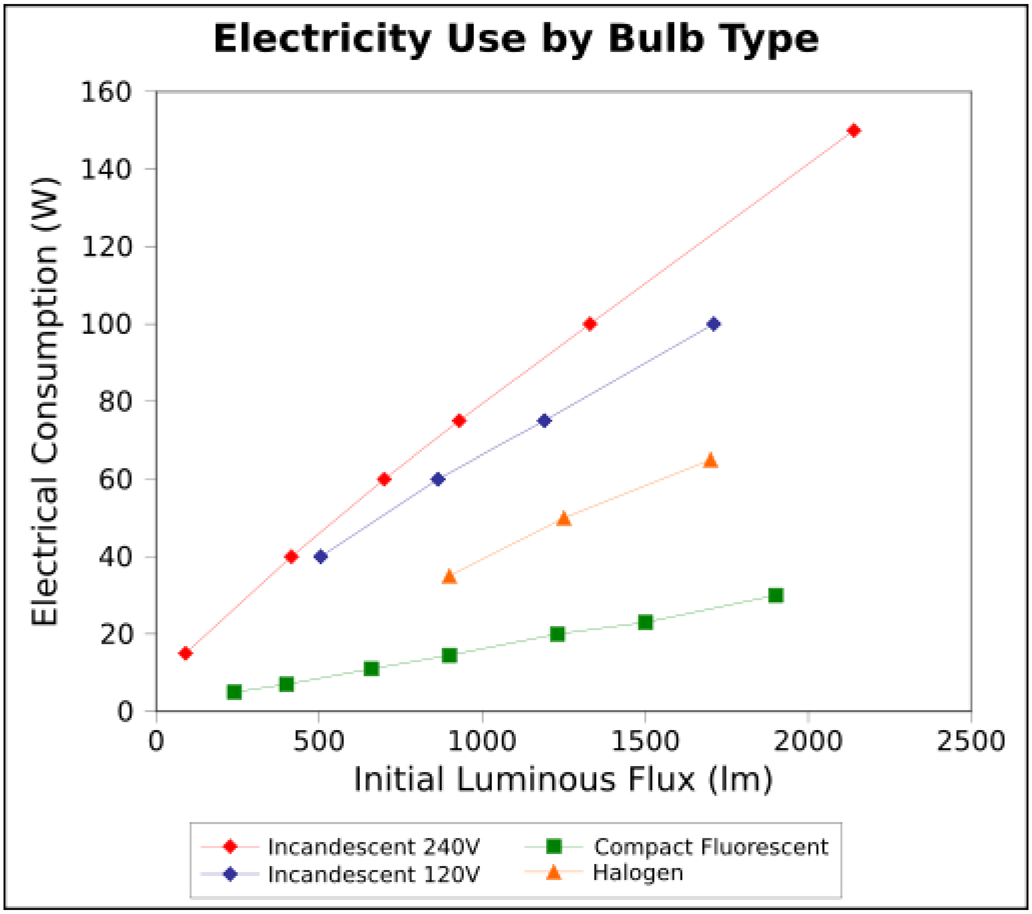
Lifespan

The average rated life of a CFL is between 8 and 15 times that of incandescents. CFLs typically have a rated lifespan of between 6,000 and 15,000 hours, whereas incandescent lamps are usually manufactured to have a lifespan of 750 hours or 1,000 hours.

The lifetime of any lamp depends on many factors including operating voltage, manufacturing defects, exposure to voltage spikes, mechanical shock, frequency of cycling on and off, lamp orientation, and ambient operating temperature, among other factors. The life of a CFL is significantly shorter if it is turned on and off frequently. In the case of a 5-minute on/off cycle the lifespan of a CFL can be reduced to "close to that of incandescent light bulbs". The US Energy Star program suggests that fluorescent lamps be left on when leaving a room for less than 15 minutes to mitigate this problem.

CFLs produce less light later in their lives than when they are new. The light output decay is exponential, with the fastest losses being soon after the lamp is first used. By the end of their lives, CFLs can be expected to produce 70–80% of their original light output. The response of the human eye to light is logarithmic (a photographic 'f-stop' reduction represents a halving in actual light, but is subjectively quite a small change). A 20–30% reduction over many thousands of hours represents a change of about half an f-stop. So, presuming the illumination provided by the lamp was ample at the beginning of its life, such a difference will be compensated for by the eyes, for most purposes.

Energy efficiency



The chart shows the energy usage for different types of light bulbs operating at different light outputs. Points lower on the graph correspond to lower energy use.

For a given light output, CFLs use 20 to 33 percent of the power of equivalent incandescent lamps. Since lighting accounted for approximately 9% of household electricity usage in the United States in 2001, widespread use of CFLs could save as much as 7% of total US household usage.

Electrical power equivalents for differing lamps

Electrical power consumption Watts (W)		**Minimum light output lumens (lm)**
Compact fluorescent	Incandescent	
9–13	40	450
13–15	60	800
18–25	75	1,100
23–30	100	1,600
30–52	150	2,600

Heating and cooling

If a building's indoor incandescent lamps are replaced by CFLs, the heat produced due to lighting is significantly reduced. In warm climates or in office or industrial buildings where air conditioning is often required, CFLs would reduce the load on the cooling system when compared to the use of incandescent lamps, resulting in savings in electricity, in addition to the energy efficiency savings of using CFLs instead of incandescent lamps. However, in cooler climates in which buildings require heating, the heating system will need to replace the inadvertently generated heat. While the CFLs are still saving electricity, total greenhouse gas emissions may increase in certain scenarios, such as the operation of a natural gas furnace to replace the unintended heating from CFLs running on low-GHG electricity. In Winnipeg, Canada, it is estimated that CFLs will only generate 17% savings in energy when switching from incandescent bulbs, as opposed to the 75% savings that can be expected if there were no heating or cooling considerations.

Efficacy and efficiency

Because the eye's sensitivity changes with the wavelength, the output of lamps is commonly measured in lumens, a measure of the power of light perceived by the human eye. The luminous efficacy of lamps refers to the number of lumens produced for each watt of electrical power used. A theoretically 100% efficient electric light source producing light only at the wavelength the human eye is most sensitive to would produce 680 lumens per watt.

The typical luminous efficacy of CFL lamps is 60 to 72 lumens per watt, and that of normal domestic incandescent lamps is 13 to 18 lm/W. Compared to the theoretical 100% efficient lamp, these figures are equivalent to lighting efficiency ranges of 9 to 11% for CFLs (60/680 and 72/680) and 1.9 to 2.6% for incandescents (13/680 and 18/680).

Embodied energy

While CFLs require more energy in manufacturing than incandescent lamps, this embodied energy is offset by their longer life and lower energy use than equivalent incandescent lamps.

Cost

While the purchase price of an integrated CFL is typically 3 to 10 times greater than that of an equivalent incandescent lamp, the extended lifetime and lower energy use will more than compensate for the higher initial cost. A US article stated "A household that invested $90 in changing 30 fixtures to CFLs would save $440 to $1,500 over the five-year life of the bulbs, depending on your cost of electricity. Look at your utility bill and imagine a 12% discount to estimate the savings."

CFLs are extremely cost-effective in commercial buildings when used to replace incandescent lamps. Using average U.S. commercial electricity and gas rates for 2006, a 2008 article found that replacing each 75 W incandescent lamp with a CFL resulted in yearly savings of $22 in energy usage, reduced HVAC cost, and reduced labour to change lamps. The incremental capital investment of $2 per fixture is typically paid back in about one month. Savings are greater and payback periods shorter in regions with higher electric rates and, to a lesser extent, also in regions with higher than U.S. average cooling requirements.

The current price of CFLs reflects the manufacturing of nearly all CFLs in China, where labour costs less. In September 2010, the Winchester, Virginia General Electric plant closed, leaving Osram Sylvania the last company to make standard incandescent bulbs in the United States. At that time, Ellis Yan, whose Chinese company made the majority of CFLs sold in the United States, was interested in building a United States factory to make CFL bulbs, but he needed $12.5 million to do so, and the U.S. government had not helped with this. Yan said stores wanted American-made bulbs, which would be 45 to 50 cents more each, but Yan said consumers were willing to pay this much.

General Electric had considered changing one of its bulb plants to make CFLs, but even after a $40 million investment, wage differences would mean the bulbs would cost one and a half times those made in China.

Comparison with alternative technologies

Solid-state lighting has already filled a few specialist niches such as traffic lights and may compete with CFLs for house lighting as well. LEDs providing over 200 lm/W have been demonstrated in laboratory tests and expected lifetimes of around 50,000 hours are typical. The luminous efficacy of available LED lamps does not typically exceed that of CFLs, though there have been LED lamps with 75 lm/W overall luminous efficacy at least since autumn 2009. DOE testing of commercial LED lamps designed to replace incandescent or CFL lamps showed that average efficacy was still about 31 lm/W in 2008 (tested performance ranged from 4 lm/W to 62 lm/W).

General Electric discontinued a 2007 development project intended to develop a high-efficiency incandescent bulb with the same lumens per watt as fluorescent lamps. Meanwhile other companies have developed and are selling halogen incandescents that use 70% of the energy of standard incandescents.

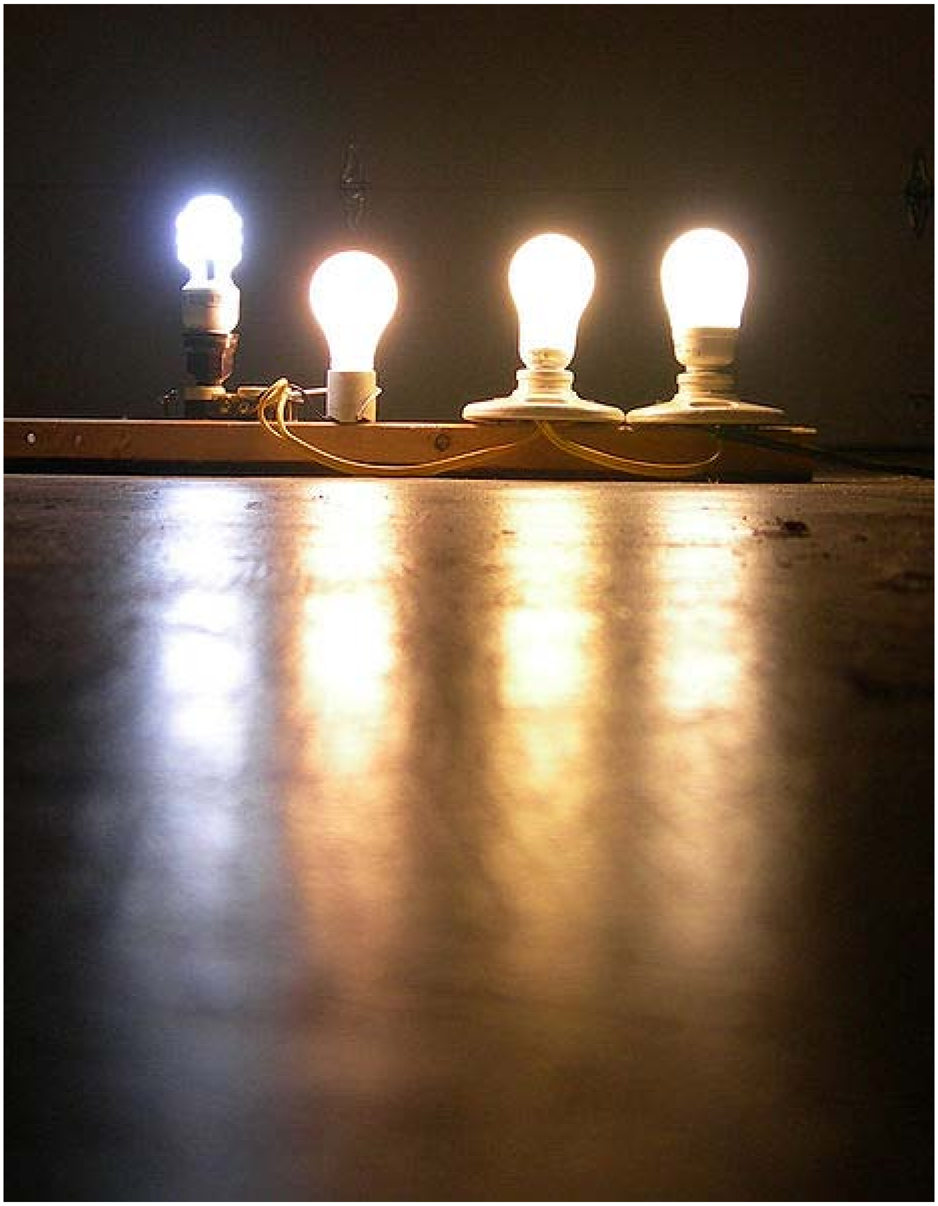
Other CFL technologies

Another type of fluorescent lamp is the electrodeless lamp, known as magnetic induction lamp, radiofluorescent lamp or fluorescent induction lamp. These lamps have no wire conductors penetrating their envelopes, and instead excite mercury vapour using a radio-frequency oscillator. Currently, this type of light source is struggling with a high cost of production, stability of the products produced by domestic manufacturers in China, establishing an internationally recognized standard and problems with EMC and RFI. Furthermore, induction lighting is excluded from Energy Star standard for 2007 by the EPA.

The cold cathode fluorescent lamp (CCFL) is one of the newest forms of CFL. CCFLs use electrodes without a filament. The voltage of CCFLs is about 5 times higher than CFLs, and the current is about 10 times lower. CCFLs have a diameter of about 3 millimeters. CCFLs were initially used for document scanners and also for back-lighting LCD displays, but they are now also manufactured for use as lamps. The efficacy (lumens per watt) is about half that of CFLs. Their advantages are that they are instant-on, like incandescents, they are compatible with timers, photocells, and dimmers, and they have a long life of approximately 50,000 hours. CCFLs are a convenient transition technology for those who are not comfortable with the short lag time associated with the initial lighting of CFLs. They are also an effective and efficient replacement for lighting that is turned on and off frequently with little extended use (e.g. a bathroom or closet).

A few manufacturers make CFL-style bulbs with mogul Edison screw bases intended to replace 250 watt and 400 watt metal halide lamps, claiming a 50% energy reduction; however, these lamps require slight rewiring of the lamp fixtures to bypass the lamp ballast.

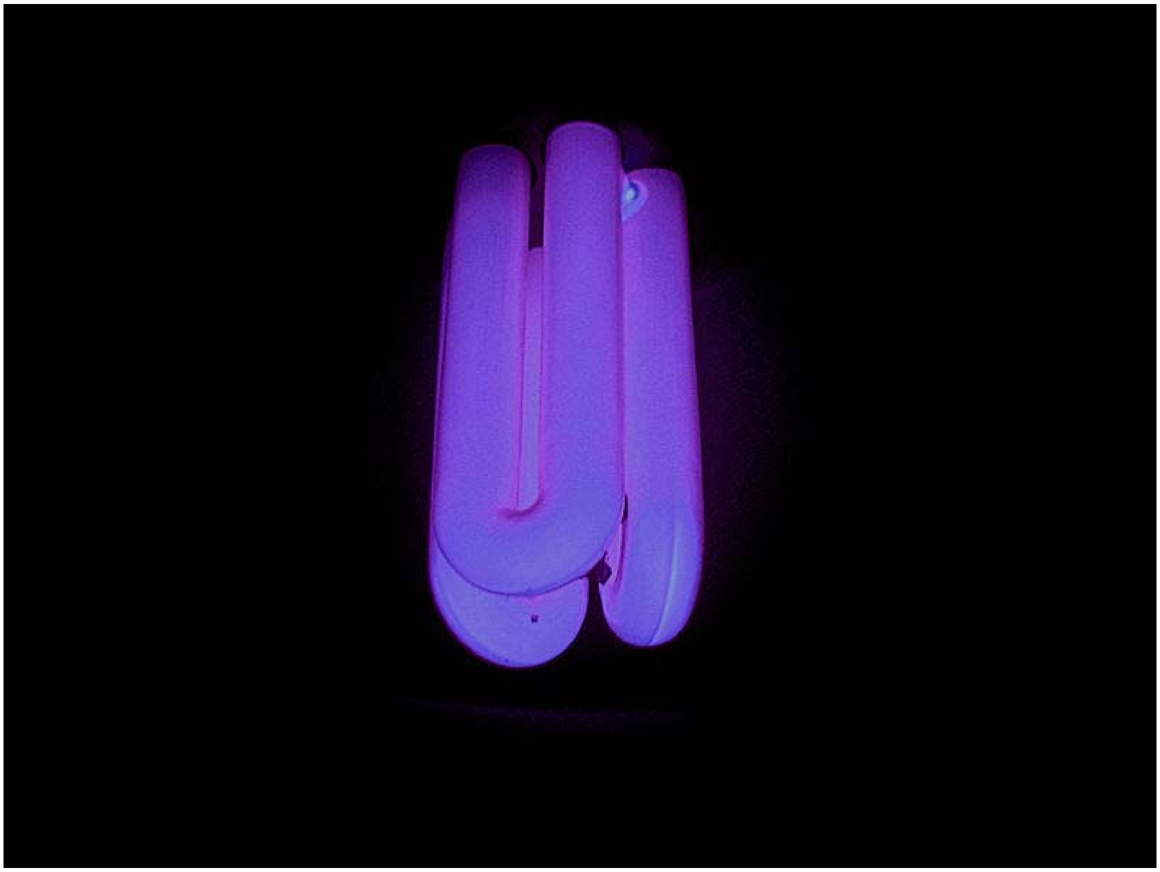
Spectrum of light



A photograph of various lamps illustrates the effect of colour temperature differences (left to right):

1. Compact Fluorescent: General Electric, 13 W, 6,500 K
2. Incandescent: Sylvania 60 W Extra Soft White
3. Compact Fluorescent: Bright Effects, 15 W, 2,644 K
4. Compact Fluorescent: Sylvania, 14 W, 3,000 K

Spectrum of a CFL bulb. The camera had a diffraction grating in front of the lens. The discrete images are produced by the different colours in the light, a line spectrum. An incandescent lamp would instead have a continuous band of colour.



A blacklight CFL.

CFLs emit light from a mix of phosphors inside the bulb, each emitting one band of colour. Modern phosphor designs are a compromise between the shade of the emitted light, energy efficiency, and cost. Every extra phosphor added to the coating mix causes a loss of efficiency and increased cost. Good quality consumer CFLs use three or four phosphors to achieve a 'white' light with a CRI (colour rendering index) of around 80, where 100 represents the appearance of colours under daylight or a black-body (depending on the correlated colour temperature).

Colour temperature can be indicated in kelvins or mireds (1 million divided by the colour temperature in kelvins).

Name	Colour temperature	
	(K)	(Mired)
Warm/soft white	≤ 3,000	≥ 333
(Bright) white	3,500	286
Cool white	4,000	250
Daylight	≥ 5,000	≤ 200

Colour temperature is a quantitative measure. The higher the number in kelvins, the more blue the shade. Colour names associated with a particular colour temperature are not standardized for modern CFLs and other tri-phosphor lamps like they were for the older-style halophosphate fluorescent lamps. Variations and inconsistencies exist among manufacturers. For example, Sylvania's Daylight CFLs have a colour temperature of 3,500 K, while most other lamps with a *daylight* label have colour temperatures of at least 5,000 K. Some vendors do not include the kelvin value on the package, but this is beginning to change now that the Energy Star criteria for CFLs is expected to require such labelling in its 4.0 revision.

Some manufacturers now label their CFLs with a 3 digit code to specify the colour rendering index (CRI) and colour temperature of the lamp. The first digit represents the CRI measured in tens of percent, while the second two digits represent the colour temperature measured in hundreds of kelvins. For example, a CFL with a CRI of 83 and a colour temperature of 2,700 K would be given a code of 827.

CFLs are also produced, less commonly, in other colours:

- Red, green, orange, blue, and pink, primarily for novelty purposes
- Blue for phototherapy
- Yellow, for outdoor lighting, because it does not attract insects
- Black light (UV light) for special effects

Black light CFLs, those with UVA generating phosphor, are much more efficient than incandescent black light lamps, since the amount of UV light that the filament of the incandescent lamp produces is only a fraction of the generated spectrum.

Disadvantages

Starting time

Incandescents reach full brightness a fraction of a second after being switched on. As of 2009, CFLs turn on within a second, but many still take time to warm up to full brightness. The light color may be slightly different immediately after being turned on. Some CFLs are marketed as "instant on" and have no noticeable warm-up period, but others can take up to a minute to reach full brightness, or longer in very cold temperatures. Some that use a mercury amalgam can take up to three minutes to reach full output. This and the shorter life of CFLs when turned on and off for short periods may make CFLs less suitable for applications such as motion-activated lighting.

Hybrid CFL

From November 2010 a Hybrid CFL as a solution for instant warm up time and brightness is commercially available. A second company announced a similar product to be available during 2011. These products combine a halogen lamp with a CFL. The halogen lights immediately, and once the CFL has warmed up the halogen lamp goes out.

Health issues

The cost effectiveness of battery-powered CFLs is enabling aid agencies to support initiatives to replace kerosene lamps, the fumes from which cause chronic lung disorders in typical homes and work places in third world countries.

According to the European Commission Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) in 2008, the only property of compact fluorescent lamps that could pose an added health risk is the ultraviolet and blue light emitted by such devices. The worst that can happen is that this radiation could aggravate symptoms in people who already suffer rare skin conditions that make them exceptionally sensitive to light. They also stated that more research is needed to establish whether compact fluorescent lamps constitute any higher risk than incandescent lamps.

If individuals are exposed to the light produced by some single-envelope compact fluorescent lamps for long periods of time at distances of less than 20 cm, it could lead to ultraviolet exposures approaching the current workplace limit set to protect workers from skin and retinal damage.

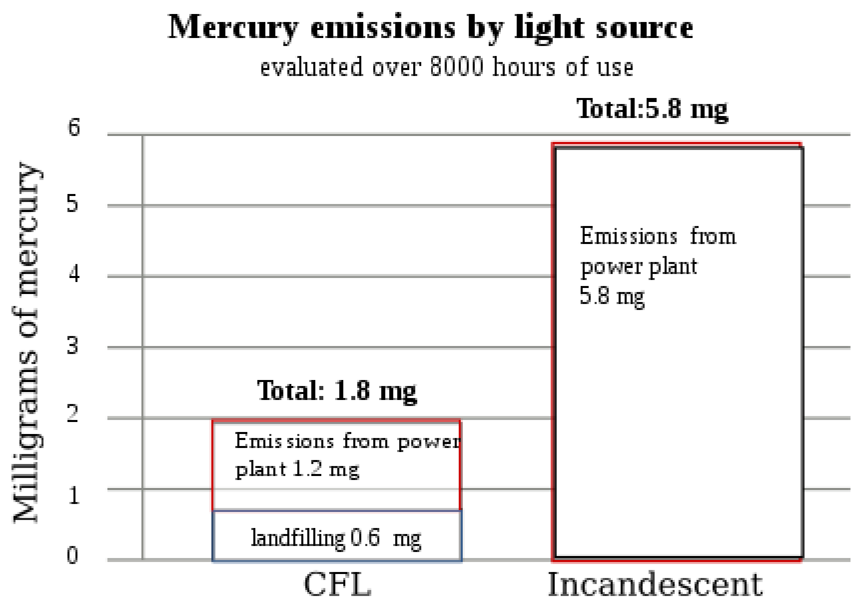
The UV radiation received from CFLs is too small to contribute to skin cancer and the use of double-envelope CFL lamps "largely or entirely" mitigates any other risks.

Environmental issues

Mercury emissions

CFLs, like all fluorescent lamps, contain small amounts of mercury as vapor inside the glass tubing. Most CFLs contain 3–5 mg per bulb, with the eco-friendly bulbs containing as little as 1 mg. Because mercury is poisonous, even these small amounts are a concern for landfills and waste incinerators where the mercury from lamps may be released and contribute to air and water pollution. In the U.S., lighting manufacturer members of the National Electrical Manufacturers Association (NEMA) have voluntarily capped the amount of mercury used in CFLs. In the EU the same cap is required by the RoHS law.

In areas with coal-fired power stations, the use of CFLs saves on mercury emissions when compared to the use of incandescent bulbs. This is due to the reduced electrical power demand, reducing in turn the amount of mercury released by coal as it is burned. In July 2008 the US EPA published a data sheet stating that the net system emission of mercury for CFL lighting was lower than for incandescent lighting of comparable lumen output. This was based on the average rate of mercury emission for US electricity production and average estimated escape of mercury from a CFL put into a landfill. Coal-fired plants also emit other heavy metals, sulphur, and carbon dioxide.



Net mercury emissions for CFL and incandescent lamps, based on EPA FAQ sheet, assuming average US emission of 0.012 mg of mercury per kilowatt-hour and 14% of CFL mercury contents escapes to environment after land fill disposal.

In the United States, the U.S. Environmental Protection Agency estimated that if all 270 million compact fluorescent lamps sold in 2007 were sent to landfill sites, that this would represent around 0.13 metric tons, or 0.1% of all U.S. emissions of mercury (around 104 metric tons that year).

Broken and discarded lamps

Health and environmental concerns about mercury have prompted many jurisdictions to require spent lamps to be properly disposed or recycled rather than being included in the general waste stream sent to landfills. It is unlawful to dispose of fluorescent bulbs as universal waste in the states of California, Minnesota, Ohio, Illinois, Indiana, Michigan, and Wisconsin. In the European Union, CFLs are one of many products subject to the WEEE recycling scheme. The retail price includes an amount to pay for recycling, and manufacturers and importers have an obligation to collect and recycle CFLs. Safe disposal requires storing the bulbs unbroken until they can be processed. In the US, The Home Depot is the first retailer to make CFL recycling options widely available.

Special handling instructions for breakage are currently not printed on the packaging of household CFL bulbs in many countries. The amount of mercury released by one bulb can temporarily exceed U.S. federal guidelines for chronic exposure. *Chronic* however, implies that the exposure continues constantly over a long period of time and the Maine DEP study noted that it remains unclear what the health risks are from short-term exposure to low levels of elemental mercury. The Maine DEP study also confirmed that, despite following EPA best-practice cleanup guidelines on broken CFLs, researchers were unable to remove mercury from carpet, and agitation of the carpet—such as by young children playing—created spikes as high as 25,000 ng/m^3 in air close to the carpet, even weeks after the initial breakage. Conventional tubular fluorescent lamps have been in commercial and domestic use since the 1930s with little public concern about their handling; these and other domestic products such as the mercury-in-glass thermometer (now banned by many countries for medical use) contain far more mercury than modern CFLs.

The U.S. Environmental Protection Agency (EPA) recommends that, in the absence of local guidelines, fluorescent bulbs be double-bagged in plastic before disposal. The Maine DEP study of 2008 compared clean-up methods, and warned that the EPA recommendation of plastic bags was the worst choice, as vapors well above safe levels continued to leach from the bags. The Maine DEP now recommends a sealed glass jar as the best repository for a broken bulb.

According to the Northwest Compact Fluorescent Lamp Recycling Project, because household users in the U.S. Northwest have the option of disposing of these products in the same way they dispose of other solid waste, in Oregon "a large majority of household CFLs are going to municipal solid waste". They also note the EPA's estimates for the percentage of fluorescent lamps' total mercury released when they are disposed of in the following ways: municipal waste landfill 3.2%, recycling 3%, municipal waste incineration 17.55% and hazardous waste disposal 0.2%.

Mercury poisoning of Chinese factory workers

In the past decade, hundreds of Chinese factory workers who manufacture CFLs for export to first world countries were being poisoned and hospitalized because of mercury exposure. Examples include workers at the Nanhai Feiyang lighting factory in Foshan where 68 out of 72 were so badly poisoned that they required hospitalization. At another CFL factory in Jinzhou, 121 out of 123 employees were found to have excessive mercury levels with one employee's mercury level 150 times the accepted standard.

Recycling

The first step of processing CFLs involves crushing the bulbs in a machine that uses negative pressure ventilation and a mercury-absorbing filter or cold trap to contain mercury vapor. Many municipalities are purchasing such machines. The crushed glass and metal is stored in drums, ready for shipping to recycling factories.

Greenhouse gases

In some parts of the world (e.g. Quebec and British Columbia) central heating for homes is provided by the burning of natural gas, whereas electricity is primarily provided by hydroelectric or nuclear power. In such areas, heat generated by conventional electric light bulbs significantly reduces the release of greenhouse gases from the natural gas. Ivanco, Karney, and Waher estimate that "If all homes in Quebec were required to switch from (incandescent) bulbs to CFLs, there would be an increase of almost 220,000 tonnes in CO_2 emissions in the province, equivalent to the annual emissions from more than 40,000 automobiles."

Design and application issues

Dimmable integrated spiral CFL that dims 2%-100%, comparable to regular light bulb dimming properties.

The primary objectives of CFL design are high electrical efficiency and durability. However, there are some other areas of CFL design and operation that are problematic:

Size

CFL light output is roughly proportional to phosphor surface area, and high output CFLs are often larger than their incandescent equivalents. This means that the CFL may not fit well in existing light fixtures.

End of life

In addition to the wear-out failure modes common to all fluorescent lamps, the electronic ballast may fail since it has a number of component parts. Ballast failures may be accompanied by discolouration or distortion of the ballast enclosure, odours, or smoke. The lamps are internally protected and are meant to fail safely at the end of their lives. Industry associations are working toward advising consumers of the different failure modes of CFLs compared to incandescent lamps, and to develop lamps with inoffensive failure modes. New North American technical standards aim to eliminate smoke or excess heat at the end of lamp life.

Incandescent replacement wattage inflation

An August 2009 newspaper report described that some manufacturers claim the CFL replaces a higher wattage incandescent lamp than justified by the light produced by the CFL. Equivalent wattage claims can be replaced by comparison of the lumens produced by the lamp.

Dimming

Only some CF lamps are labelled for dimming control. Using regular CFLs with a dimmer is ineffective at dimming, can shorten bulb life and will void the warranty of certain manufacturers. Dimmable CFLs are available. There is a need for the dimmer switch used in conjunction with a dimmable CFL to be matched to its power consumption range, many dimmers installed for use with incandescent bulbs do not yield acceptable results below 40W, whereas CFL applications commonly draw power in the range 7-20W. The marketing and availability of dimmable CFLs has preceded that of suitable dimmers. The dimming range of CFLs is usually between 20% and 90%. However, in many modern CFLs the dimmable range has been improved to be from 2% to 100%, more akin to regular lights. There are two types of dimmable CFL marketed: Regular dimmable CFLs, and "switch-dimmable" CFLs. The latter use a regular light switch, while the on-board electronics has a setting where the number of times the switch is turned on & off in quick succession sets a reduced light output mode. Dimmable CFLs are not a 100% replacement for incandescent fixtures that are dimmed for "mood scenes" such as wall sconces in a dining area. Below the 20% limit, the lamp remain at the approximate 20% level, in other cases it may flicker or the starter circuitry may stop and restart. Above the 80% dim limit, the bulb will generally glow at 100% brightness. However, these issues have been addressed with the latest units and some CFLs may perform more like regular lamps. Dimmable CFLs have a higher purchase cost than standard CFLs due to the additional circuitry required for dimming. A further limitation is that multiple dimmable CFLs on the same dimmer switch may not appear to be at the same brightness level. Cold Cathode CFLs can be dimmed to low levels, making them popular replacements for incandescent bulbs on dimmer circuits.

Perceived coldness of low intensity CFL

When a CFL is dimmed the colour temperature (warmth) stays the same. This is counter to most other light sources (such as the sun or incandescents) where colour gets warmer as the light source gets dimmer. Emotional response testing suggests that people find dim, bluish light sources to be cold or even sinister. This may explain the persistent lack of popularity for CFLs in bedrooms and other settings where a subdued light source is preferred.

Heat

Some CFLs are labelled not to be run base up, since heat will shorten the ballast's life. Such CFLs are unsuitable for use in pendant lamps and especially unsuitable for recessed light fixtures. CFLs for use in such fixtures are available. Current recommendations for fully enclosed, unventilated light fixtures (such as those recessed into insulated ceilings), are either to use 'reflector CFLs' (R-CFL), cold cathode CFLs or to replace such fixtures with those designed for CFLs. A CFL will thrive in areas that have good airflow, such as in a table lamp.

Power quality

The introduction of CFLs may affect power quality appreciably, particularly in large-scale installations. The input stage of a CFL is a rectifier, which presents a non-linear load to the power supply and introduces harmonic distortion on the current drawn from the supply. In such cases, CFLs with low (below 30 percent) total harmonic distortion (THD) and power factors greater than 0.9 should be used.

Infra-red signals

Electronic devices operated by infra-red remote control can interpret the infra-red light emitted by CFLs as a signal, this limits the use of CFLs near televisions, radios, remote controls, or mobile phones.

Iridescence

Fluorescent lamps can cause window film to exhibit iridescence. This phenomenon usually occurs at night. The amount of iridescence may vary from almost imperceptible, to very visible and most frequently occurs when the film is constructed using one or more layers of sputtered metal. It can however occur in non-reflective films as well. When iridescence does occur in window film, the only way to stop it is to prevent the fluorescent light from illuminating the film.

Use with timers, motion sensors, light sensors, and other electronic controls

Some electronic (but not mechanical) timers can interfere with the electronic ballast in CFLs and can shorten their lifespan. Some timers rely on a connection to neutral through the bulb and so pass a tiny current through the bulb, charging the capacitors in the electronic ballast. They may not work with a CFL connected, unless an incandescent bulb is also connected. They may also cause the CFL to flash when off. This can also be true for illuminated wall switches and motion sensors. Also, most CFLs will not work with light sensor devices, as in a "dusk to dawn" device. Cold cathode CFLs avoid many of these problems. Timer manufacturers may make products compatible with CFL lamps.

Fire hazard

When the base of the bulb is not made to be flame-retardant, as required in the voluntary standard for CFLs, then the electrical components in the bulb can overheat which poses a fire hazard. The latest ENERGY STAR CFL specification (which went into effect December 2, 2008) requires all ENERGY STAR qualified CFLs to incorporate end-of-life requirements and higher safety standards. The Electrical Safety Authority of Canada has stated that certified bulbs do not pose a fire hazard as they use anti-fire plastics.

Outdoor use

CFLs are generally not designed for outdoor use and some will not start in cold weather. CFLs are available with cold-weather ballasts, which may be rated to as low as −23 °C (−10 °F). Light output drops at low temperatures. Cold cathode CFLs will start and perform in a wide range of temperatures due to their different design.

Differences among manufacturers

There are large differences among quality of light, cost, and turn-on time among different manufacturers, even for lamps that appear identical and have the same colour temperature.

Lifetime brightness

Fluorescent lamps get dimmer over their lifetime, so what starts out as an adequate luminosity may become inadequate. In one test by the US Department of Energy of 'Energy Star' products in 2003–04, one quarter of tested CFLs no longer met their rated output after 40% of their rated service life.

UV emissions

Fluorescent bulbs can damage paintings and textiles which have light-sensitive dyes and pigments. Strong colours will tend to fade on exposure to UV light. Ultraviolet light can also cause polymer degradation with a loss in mechanical strength and yellowing of colourless products.

Efforts to encourage adoption

Due to the potential to reduce electric consumption and pollution, various organizations have encouraged the adoption of CFLs and other efficient lighting. Efforts range from publicity to encourage awareness, to direct handouts of CFLs to the public. Some electric utilities and local governments have subsidized CFLs or provided them free to customers as a means of reducing electric demand (and so delaying additional investments in generation).

More controversially, some governments are considering stronger measures to entirely displace incandescents. These measures include taxation, or bans on production of incandescent light bulbs that do not meet energy efficiency requirements.

In 2008, the European Union approved regulations progressively phasing out incandescent bulbs starting in 2009 and finishing at the end of 2012. By switching to energy saving bulbs, EU citizens will save almost 40 TW·h (almost the electricity consumption of 11 million European households), leading to a reduction of about 15 million metric tons of CO_2 emissions per year.

Australia, Canada, and the United States have also announced plans for nationwide efficiency standards that would constitute an effective ban on most current incandescent bulbs.

Venezuela and Cuba have launched massive incandescent light bulbs replacement programs in order to save energy. In the case of Venezuela, the government was able to save 2000 MW of electricity in the first six months of the 2006 program called Mission Energy Revolution, which by 2007 replaced 20 million incandescent light bulbs with CFL from a total of an estimated 55 million light bulbs in the country. Cuba replaced all the 11 million light bulbs used in the island. Also, Venezuela signed an agreement with Vietnam, one of the large producers of CFLs in the world, to establish a factory to supply the future demand and hand-outs of government light bulbs.

The United States Department of Energy reports that sales of CFLs have dropped between 2007 and 2008, and estimated only 11% of suitable domestic light sockets use CFLs.

In the USA, the *Program for the Evaluation and Analysis of Residential Lighting* (PEARL) was created to be a watchdog program. PEARL has evaluated the performance and ENERGY STAR compliance of more than 150 models of CFL bulbs.

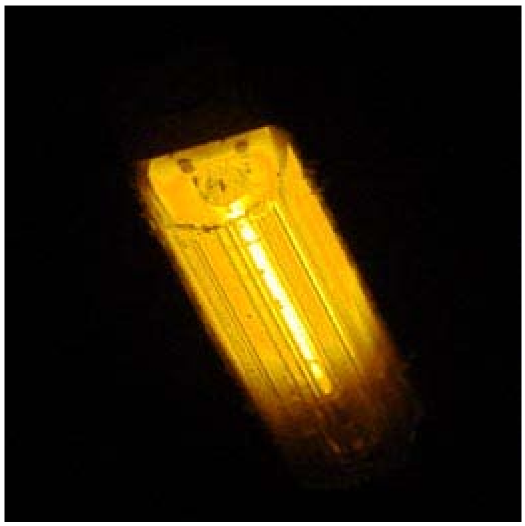
Labeling programs

In the United States and Canada, the Energy Star program labels compact fluorescent lamps that meet a set of standards for starting time, life expectancy, color, and consistency of performance. The intent of the program is to reduce consumer concerns due to variable quality of products. Those CFLs with a recent Energy Star certification start in less than one second and do not flicker. There is ongoing work in improving the 'quality' (color rendering index) of the light.

In the United Kingdom a similar program is run by the Energy Saving Trust to identify lighting products that meet energy conservation and performance guidelines.

Chapter- 4

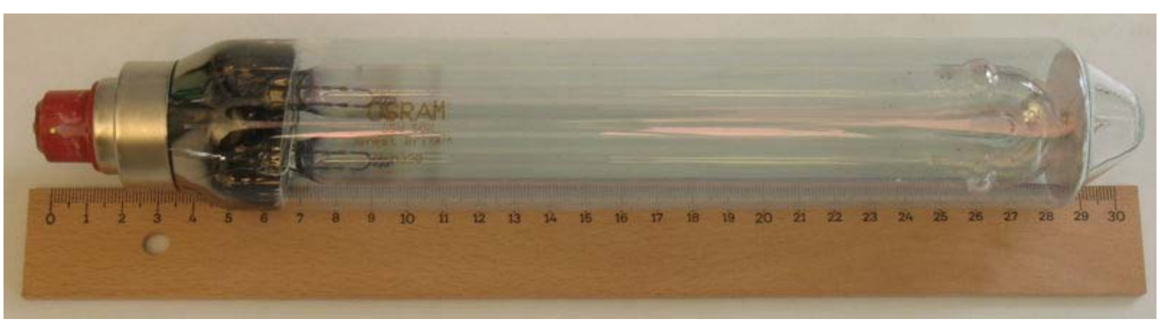
Sodium-Vapor Lamp



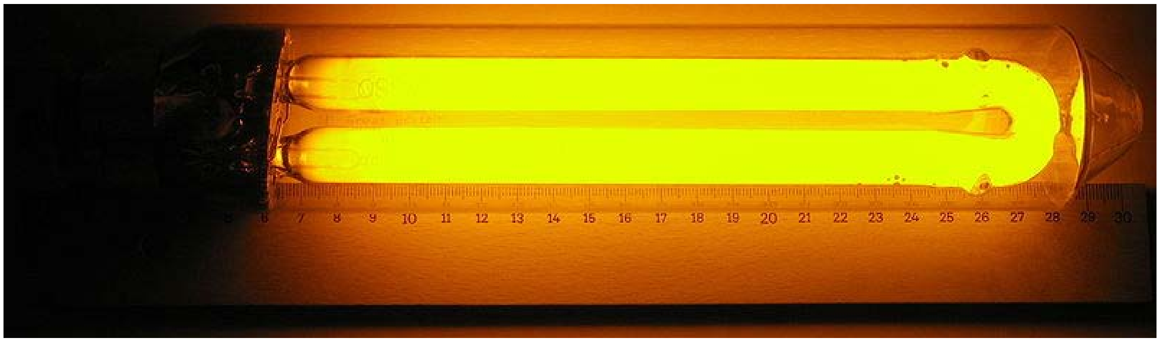
A low pressure sodium streetlamp at full power

A **sodium vapor lamp** is a gas discharge lamp that uses sodium in an excited state to produce light. There are two varieties of such lamps: *low pressure* and *high pressure*. Because **sodium vapor lamps** cause less light pollution than mercury-vapor lamps, many cities that have large astronomical observatories employ them.

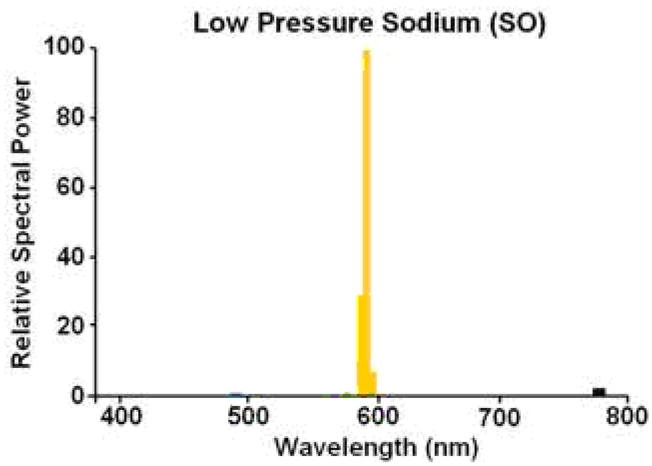
Low pressure sodium



An unlit 35W LPS/SOX lamp



A running 35W LPS/SOX lamp



Spectrum of a low-pressure sodium lamp. The intense yellow band is the atomic sodium D-line emission, comprising about 90% of the visible light emission for this lamp type.

Low-pressure sodium (LPS) lamps have a borosilicate glass gas discharge tube (arc tube) containing solid sodium and a small amount of neon and argon gas Penning mixture to start the gas discharge. The discharge tube may be linear (SLI lamp) or U-shaped. When the lamp is turned on it emits a dim red/pink light to warm the sodium metal and within a few minutes it turns into the common bright yellow as the sodium metal vaporizes. These lamps produce a virtually monochromatic light averaging a 589.3 nm wavelength (actually two dominant spectral lines very close together at 589.0 and 589.6 nm). As a result, the colors of illuminated objects are not easily distinguished because they are seen almost entirely by their reflection of this narrow bandwidth yellow light.

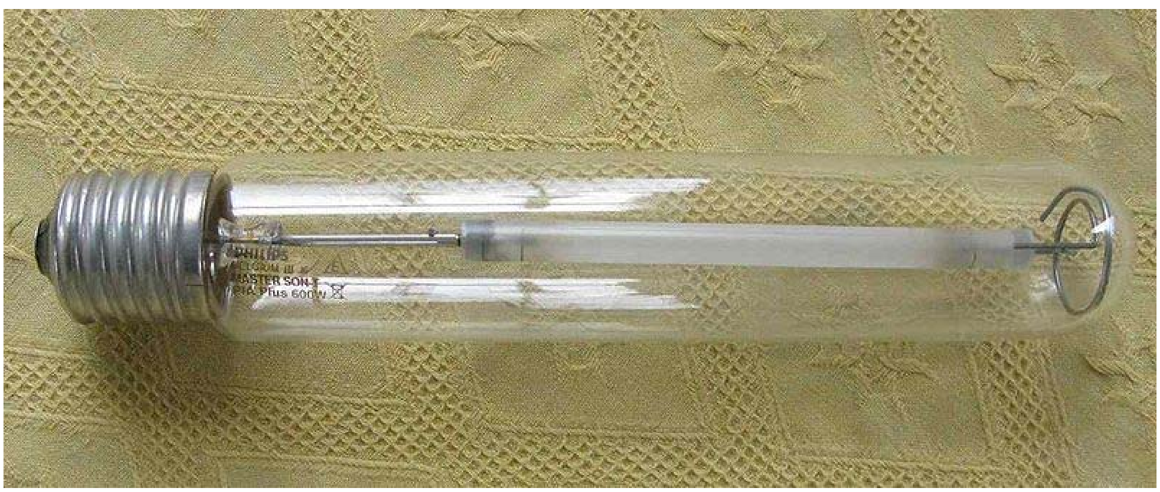
LPS lamps have an outer glass vacuum envelope around the inner discharge tube for thermal insulation, which improves their efficiency. Earlier types of LPS lamps had a detachable dewar jacket (SO lamps). Lamps with a permanent vacuum envelope (SOI lamps) were developed to improve thermal insulation . Further improvement was attained by coating the glass envelope with an infrared reflecting layer of indium tin oxide, resulting in SOX lamps.

LPS lamps are the most efficient electrically-powered light source when measured for photopic lighting conditions—up to 200 lm/W, primarily because the output is light at a wavelength near the peak sensitivity of the human eye. As a result they are widely used for outdoor lighting such as street lights and security lighting where faithful color rendition is considered unimportant. LPS lamps are available with power ratings from 10 W up to 180 W; however, longer bulb lengths create design and engineering problems.

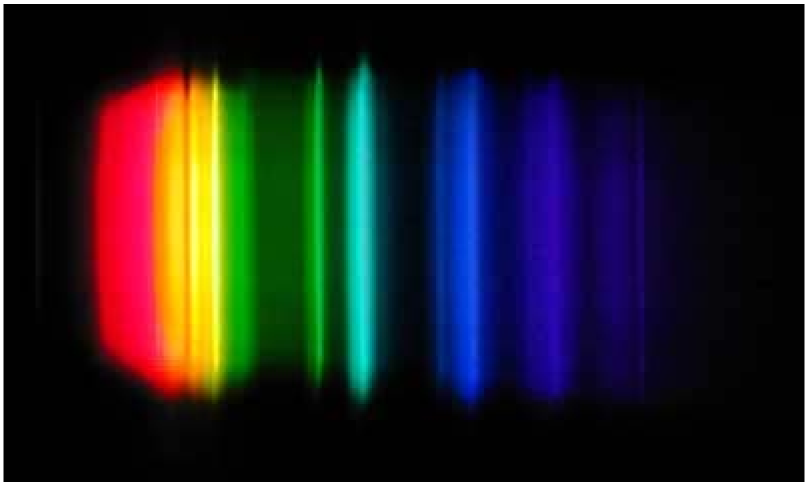
LPS lamps are more closely related to fluorescent than high intensity discharge lamps because they have a low–pressure, low–intensity discharge source and a linear lamp shape. Also like fluorescents they do not exhibit a bright arc as do other HID lamps; rather they emit a softer luminous glow, resulting in less glare. Unlike HID lamps, which can go out during a voltage dip, low pressure sodium lamps restrike to full brightness rapidly.

Another unique property of LPS lamps is that, unlike other lamp types, they do not decline in lumen output with age. As an example, mercury vapor HID lamps become very dull towards the end of their lives, to the point of being ineffective, while continuing to consume full rated electrical use. LPS lamps, however, do increase energy usage slightly (about 10%) towards their end of life, which is generally around 18,000 hours for modern lamps.

High pressure sodium



High pressure sodium lamp Philips SON-T Master 600W



Spectrum of high pressure sodium lamp. The yellow-red band on the left is the atomic sodium D-line emission; the turquoise line is a sodium line that is otherwise quite weak in a low pressure discharge, but become intense in a high pressure discharge. Most of the other green, blue and violet lines arise from mercury.

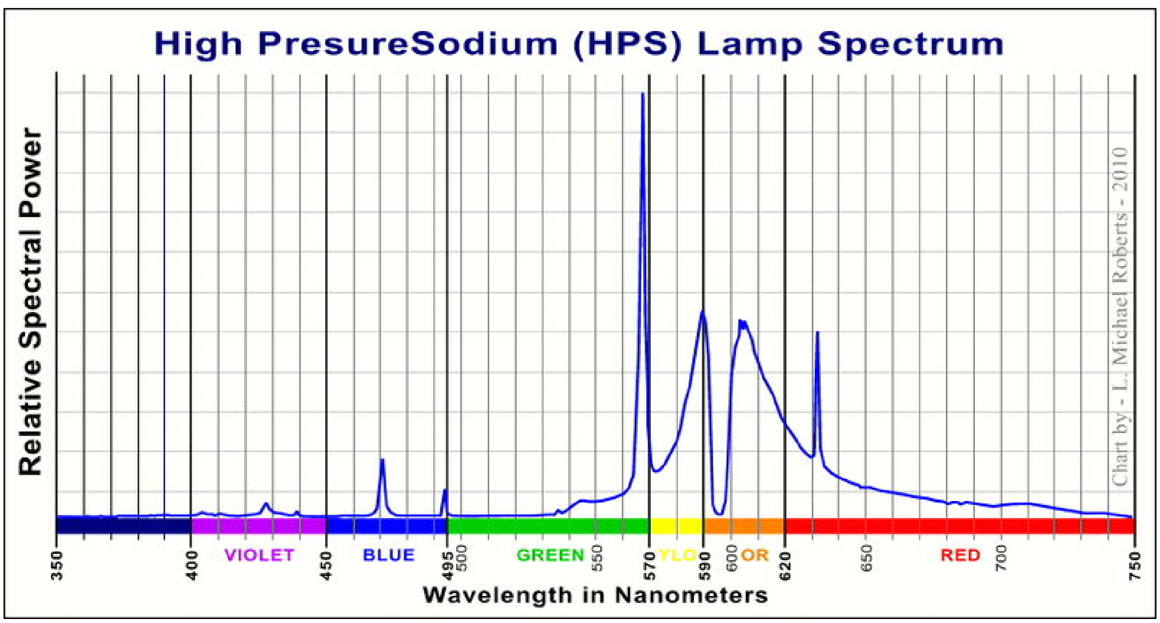


Diagram showing the spectral output of a typical high pressure sodium (HPS) lamp

Office building illuminated by high pressure sodium lamps

High-pressure sodium (HPS) lamps are smaller and contain additional elements such as mercury, and produce a dark pink glow when first struck, and a pinkish orange light when warmed. Some bulbs also briefly produce a pure to bluish white light in between. This is probably from the mercury glowing before the sodium is completely warmed. The sodium D-line is the main source of light from the HPS lamp, and it is extremely pressure broadened by the high sodium pressures in the lamp; because of this broadening and the emissions from mercury, colors of objects under these lamps can be distinguished. This leads them to be used in areas where good color rendering is important, or desired. Thus, its new model name SON is the variant for "sun" (a name used primarily in Europe and the UK). HPS Lamps are favoured by indoor gardeners for general growing because of the wide colour-temperature spectrum produced and the relatively efficient cost of running the lights.

High pressure sodium lamps are quite efficient—about 100 lm/W—when measured for photopic lighting conditions. They have been widely used for outdoor lighting such as streetlights and security lighting. Understanding the change in human color vision sensitivity from *photopic* to *mesopic* and *scotopic* is essential for proper planning when designing lighting for roads.

Because of the extremely high chemical activity of the high pressure sodium arc, the arc tube is typically made of translucent aluminium oxide. This construction led General Electric to use the tradename "Lucalox" for their line of high-pressure sodium lamps.

Xenon at a low pressure is used as a "starter gas" in the HPS lamp. It has the lowest thermal conductivity and lowest ionization potential of all the non-radioactive noble gases. As a noble gas, it does not interfere with the chemical reactions occurring in the operating lamp. The low thermal conductivity minimizes thermal losses in the lamp while in the operating state, and the low ionization potential causes the breakdown voltage of the gas to be relatively low in the cold state, which allows the lamp to be easily started.

"White" SON

A variation of the high pressure sodium, the White SON, introduced in 1986, has a higher pressure than the typical HPS/SON lamp, producing a color temperature of around 2700 K, with a CRI of 85; greatly resembling the color of an incandescent light. These are often used indoors in cafes and restaurants to create a particular atmosphere. However, these lamps suffer from higher purchase cost, shorter life, and lower light efficiency.

Theory of operation

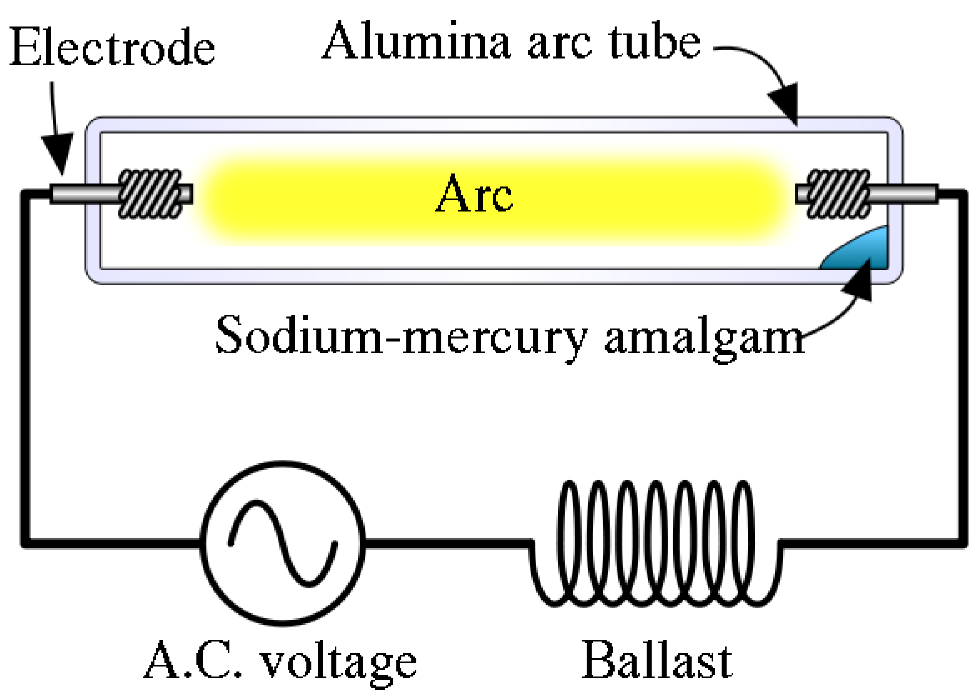


Diagram of a high pressure sodium lamp

An amalgam of metallic sodium and mercury lies at the coolest part of the lamp and provides the sodium and mercury vapor that is needed to draw an arc. The temperature of the amalgam is determined to a great extent by lamp power. The higher the lamp power, the higher will be the amalgam temperature. The higher the temperature of the amalgam, the higher will be the mercury and sodium vapor pressures in the lamp. An increase in these metal pressures will cause an increase in the electrical resistance of the lamp. As the temperature rises, the flow of current being maintained constant results in an increase in power until the nominal power is reached. For a given voltage, there are generally three modes of operation:

1. The lamp is extinguished and no current flows.
2. The lamp is operating with liquid amalgam in the tube.
3. The lamp is operating with all amalgam evaporated.

The first and last states are stable, because the lamp resistance is weakly related to the voltage, but the second state is unstable. Any anomalous increase in current will cause an increase in power, causing an increase in amalgam temperature, which will cause a decrease in resistance, which will cause a further increase in current. This will create a runaway effect, and the lamp will jump to the high-current state (#3). Because actual lamps are not designed to handle this much power, this would result in catastrophic failure. Similarly, an anomalous drop in current will drive the lamp to extinction. It is the second state that is the desired operating state of the lamp, because a slow loss of the amalgam over time from a reservoir will have less effect on the characteristics of the lamp than a fully evaporated amalgam. The result is an average lamp life in excess of 20,000 hours.

In practical use, the lamp is powered by an AC voltage source in series with an inductive "ballast" in order to supply a nearly constant current to the lamp, rather than a constant voltage, thus assuring stable operation. The ballast is usually inductive rather than simply being resistive to minimize resistive losses. Because the lamp effectively extinguishes at each zero-current point in the AC cycle, the inductive ballast assists in the reignition by providing a voltage spike at the zero-current point.

The light from the lamp consists of atomic emission lines of mercury and sodium, but is dominated by the sodium D-line emission. This line is extremely pressure (resonance) broadened and is also self-reversed because of absorption in the cooler outer layers of the arc, giving the lamp its improved color rendering characteristics. In addition, the red wing of the D-line emission is further pressure broadened by the Van der Waals forces from the mercury atoms in the arc.

Light pollution considerations

For placements where light pollution is of prime importance, such as an astronomical observatory parking lot, or a large city nearby an astronomical observatory, low pressure sodium is preferred. Such lamps emit light on just one dominant spectral line (with other far-weaker lines), and therefore is the easiest to filter out. One consequence of widespread public lighting is that on cloudy nights, cities with enough lighting are illuminated by light reflected off the clouds. As sodium vapor lights are often the source of urban illumination, this turns the sky a tinge of orange. If the sky is clear or hazy, the light will radiate over large distances, causing large enough cities to be recognizable by an orange glow when viewed from outside the city.

End of life

At the end of life, high-pressure sodium lamps exhibit a phenomenon known as *cycling*, which is caused by a loss of sodium in the arc. Sodium is a highly reactive element, and is easily lost by reacting with the arc tube made of aluminum oxide and the products are sodium oxide and aluminum:

$$6\ Na + Al_2O_3 \rightarrow 3\ Na_2O + 2\ Al$$

As a result, these lamps can be started at a relatively low voltage but as they heat up during operation, the internal gas pressure within the arc tube rises and more and more voltage is required to maintain the arc discharge. As a lamp gets older, the maintaining voltage for the arc eventually rises to exceed the maximum voltage output by the electrical ballast. As the lamp heats to this point, the arc fails and the lamp goes out. Eventually, with the arc extinguished, the lamp cools down again, the gas pressure in the arc tube is reduced, and the ballast can once again cause the arc to strike. The effect of this is that the lamp glows for a while and then goes out, repeatedly.

More sophisticated ballast designs detect cycling and give up attempting to start the lamp after a few cycles, as the repeated high voltage ignitions needed to restart the arc reduces the lifetime of the ballast. If power is removed and reapplied, the ballast will make a new series of startup attempts.

LPS lamp failure does not result in cycling; rather, the lamp will simply not strike or will maintain its dull red glow exhibited during the start up phase.

Chapter- 5

Electrodeless Lamp

An **electrodeless lamp** is a light source in which the power required to generate light is transferred from the outside of the lamp envelope by means of (electro)magnetic fields, in contrast with a typical electrical lamp that uses electrical connections through the lamp envelope to transfer power. There are three advantages of eliminating electrodes:

- Extended lamp life, because the electrodes are usually the limiting factor in lamp life.
- The ability to use high efficiency light-generating substances that would react with metal electrodes in normal lamps.
- Improved collection efficiency because the source can be made very small without shortening life - a problem in electroded lamps

Two systems are described below—one, plasma lamps, based on the use of radio waves energizing a bulb filled with sulfur or metal halides, the other, fluorescent induction lamps, based upon conventional fluorescent lamp phosphors.

History

Nikola Tesla demonstrated wired and wireless transfer of power to electrodeless fluorescent and incandescent lamps in his lectures and articles in the 1890s, and subsequently patented a system of light and power distribution on those principles. In the lecture before the AIEE, May 20, 1891, titled *Experiments with Alternating Currents of Very High Frequency and Their Application to Methods of Artificial Illumination* and US patent 454622, among many other references in the technical and popular press are found countless records for Tesla's priority in this field. A suit filed by Tesla against J. J. Thomson for priority on the patent was subsequently granted in Tesla's favor. The transcripts of the case languish currently in archives, awaiting processing, and eventual publishing. Noting the diagrams in Tesla's lectures and patents, a striking similarity of construction to electrodeless lamps that are available on the market currently is readily apparent. Further, a statement in 1929 by Tesla, published in The World :

Surely, my system is more important than the incandescent lamp, which is but one of the known electric illuminating devices and admittedly not the best. Although greatly improved through chemical and metallurgical advances and skill of artisans it is still inefficient, and the glaring filament emits hurtful rays responsible for millions of bald heads and spoiled eyes. In my opinion, it will soon be superseded by the electrodeless vacuum tube which I brought out thirty-eight years ago, a lamp much more economical and yielding a light of indescribable beauty and softness.

In 1967 and 1968, John Anderson of General Electric applied for patents for electrodeless lamps. Philips introduced their *QL* induction lighting systems, operating at 2.65 MHz, in 1990 in Europe and in 1992 in the US. Matsushita had induction light systems available in 1992. Intersource Technologies also announced one in 1992, called the *E-lamp*. Operating at 13.6 MHz, it was to be available on the US market in 1993 but as of July 2005 very few of these lamps have been manufactured.

In 1990, Michael Ury, Charles Wood and colleagues, formulated the concept of the sulphur lamp. With support from the United States Department of Energy, it was further developed in 1994 by Fusion Lighting of Rockville, Maryland, a spinoff of the Fusion UV division of Fusion Systems Corporation. Its origins are in microwave discharge light sources used for ultraviolet curing in the semiconductor and printing industries.

Since 1994, General Electric has produced its induction lamp *Genura* with an integrated ballast, operating at 2.65 MHz. In 1996, Osram started selling their *Endura* induction light system, operating at 250 kHz. It is available in the US as the Sylvania *Icetron*.

From 1995, the former distributors of Fusion, Jenton / Jenact, expanded on the fact that energised UV-emitting plasmas act as lossy conductors to create a number of patents with respect to electrodeless UV lamps in the sterilisation / germicidal field.

Around 2000 a system was developed that concentrated radio frequency waves into a solid dielectric waveguide made of ceramic which energized a light emitting plasma in a bulb positioned inside. This system, for the first time, permitted an extremely bright and compact electrodeless lamps. The invention has been a matter of dispute. Claimed by Frederick Espiau (then of Luxim now of Topanga Technologies), Chandrashekhar Joshi and Yian Chang, these claims were disputed by Ceravision Limited. Recently a number of the core patents were assigned to Ceravision.

In 2006 Luxim introduced a projector lamp product trade-named LIFI. The company further extended the technology with light source products in instrument, entertainment, street, area and architectural lighting applications among others throughout 2007 and 2008.

In 2009 Ceravision Limited introduced the first High Efficiency Plasma (HEP) lamp under the trade name Alvara. This lamp replaces the opaque ceramic waveguide used in earlier lamps with an optically clear quartz waveguide giving greatly increased efficiency. In previous lamps, though the burner, or bulb, was very efficient, the opaque ceramic waveguide severely obstructed the collection of light. A quartz waveguide allows all of the light from the plasma to be collected.

Plasma lamps

Plasma lamps are a family of light sources that generate light by exciting a plasma inside a closed transparent burner or bulb using radio frequency (RF) power. Typically, such lamps use a noble gas or a mixture of these gases and additional materials such as metal halides, sodium, mercury or sulfur. A waveguide is used to constrain and focus the electrical field into the plasma. In operation the gas is ionized and free electrons, accelerated by the electrical field collide with gas and metal atoms. Some electrons circling around the gas and metal atoms are excited by these collisions, bringing them to a higher energy state. When the electron falls back to its original state, it emits a photon, resulting in visible light or ultraviolet radiation depending on the fill materials.

The first plasma lamp was an ultraviolet curing lamp with a bulb filled with argon and mercury vapor developed by Fusion UV. That lamp led Fusion Systems to the development of the sulfur lamp, a bulb filled with argon and sulfur which is bombarded with microwaves through a hollow waveguide.

In the past, the reliability of the technology was limited by the magnetron used to generate the microwaves. Solid state RF generation can be used and gives long life. However, using solid state chips to generate RF is approximately fifty times more expensive currently than using a magnetron and so only appropriate for high value lighting niches. It has recently been shown by Dipolar of Sweden to be possible to greatly extend the life of magnetrons to over 40,000 hours making low cost plasma lamps possible. Plasma lamps are currently produced by Ceravision and Luxim and in development by Topanga Technologies.

Ceravision has introduced a combined lamp and luminaire under the trade name *Alvara* for use in high bay and street lighting applications. It uses an optically clear quartz waveguide with an integral burner allowing all the light from the plasma to be collected. The small source also allows the luminaire to utilize more than 90% of the available light compared with 55% for typical HID fittings. Ceravision claims the highest Luminaire Efficacy Rating (LER) of any light fitting on the market and to have created the first High Efficiency Plasma (HEP) lamp. Ceravision uses a magnetron to generate the required RF power and claim a life of 20,000 hours.

Luxim's LIFI, or light fidelity lamp, claims 120 lumens per RF watt (ie before taking into account electrical losses). The lamp has been used in Robe lighting's *ROBIN 300 Plasma Spot* moving headlight. It was also used in a line of, now discontinued, Panasonic rear projection TV's.

Magnetic induction lamps

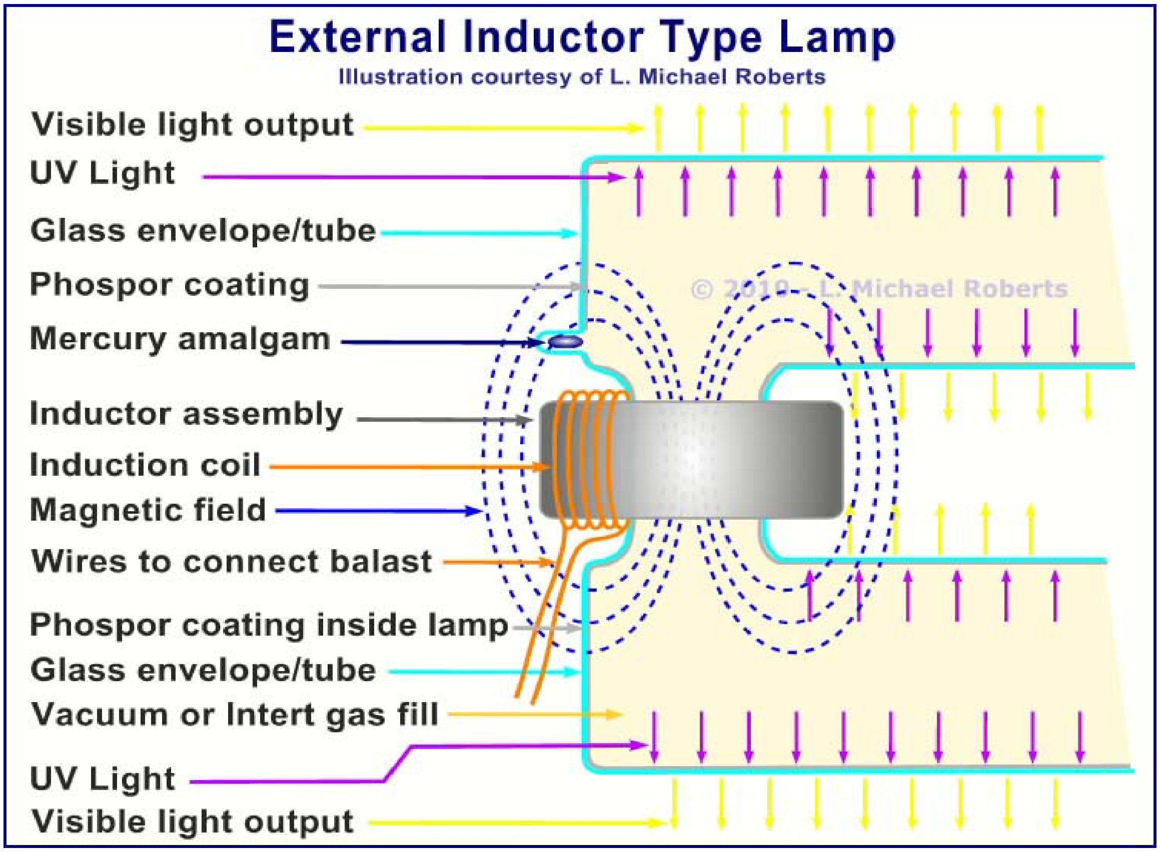
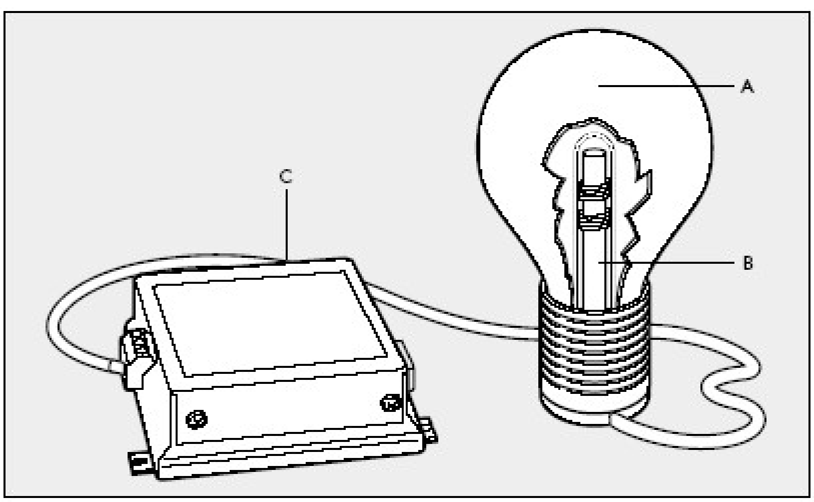


Diagram showing labelled components of a rectangular style, external inductor type, Magnetic Induction Lamp (ballast not shown).



A Philips QL induction lighting system, where A) *Discharge vessel*, B) *Tube with power coupler* and C) *Electronic ballast*

Aside from the method of coupling energy into the mercury vapour, these lamps are very similar to conventional fluorescent lamps. Mercury vapour in the discharge vessel is electrically excited to produce short-wave ultraviolet light, which then excites the phosphors to produce visible light. While still relatively unknown to the public, these lamps have been available since 1990. The first type introduced had the shape of an incandescent light bulb. Unlike an incandescent lamp or conventional fluorescent lamps, there is no electrical connection going inside the glass bulb; the energy is transferred *through* the glass envelope solely by electromagnetic induction.

There are two main types of magnetic induction lamp, external inductor lamps and internal inductor lamps. The original, and still widely used form of induction lamps are the internal inductor types. A more recent development is the external inductor types which have a wider range of applications and which are available in round, rectangular and "olive" shaped form factors.

External inductor lamps are basically fluorescent lamps with electromagnets wrapped around a part of the tube. In the external inductor lamps, high frequency energy, from the electronic ballast, is sent through wires, which are wrapped in a coil around a ferrite inductor on the outside of the glass tube, creating a powerful electromagnet called an inductor. The induction coil (inductor) produces a very strong magnetic field which travels through the glass and excites the mercury atoms in the interior. The mercury atoms are provided by the amalgam (a solid form of mercury). The excited mercury atoms emit UV light and, just as in a fluorescent tube, the UV light is down-converted to visible light by the phosphor coating on the inside of the tube. The glass walls of the lamp prevent the emission of the UV light as ordinary glass blocks UV radiation at the 253.7 nm and 185 nm range.

In the internal inductor form, a glass tube (B) protrudes bulb-wards from the bottom of the discharge vessel (A), forming a re-entrant cavity. This tube contains an antenna called a *power coupler*, which consists of a coil wound over a tubular ferrite core. The coil and ferrite forms the inductor which couples the energy into the lamp interior

The antenna coils receive electric power from the electronic ballast (C) that generates a high frequency. The exact frequency varies with lamp design, but popular examples include 13.6 MHz, 2.65 MHz and 250 kHz. A special resonant circuit in the ballast produces an initial high voltage on the coil to start a gas discharge; thereafter the voltage is reduced to normal running level.

The system can be seen as a type of transformer, with the power coupler (inductor) forming the primary coil and the gas discharge arc in the bulb forming the one-turn secondary coil and the load of the transformer. The ballast is connected to mains electricity, and is generally designed to operate on voltages between 100 and 277 VAC at a frequency of 50 or 60 Hz. Many ballasts are available in low voltage models so can also be connected to DC voltage sources like batteries for emergency lighting purposes of for use with renewable energy (solar & wind) powered systems.

In other conventional gas discharge lamps, the electrodes are the part with the shortest life, limiting the lamp lifespan severely. Since an induction lamp has no electrodes, it can have a very long service life. For induction lamp systems with a separate ballast, the service life can be as long as 100,000 hours, which is 11.4 years continuous operation. For induction lamps with integrated ballast, the lifespan is in the 15,000 to 50,000 hours range. Extremely high-quality electronic circuits are needed for the ballast to attain such a long service life. Such lamps are typically used in commercial or industrial applications. Typically operations and maintenance costs are significantly lower with induction lighting systems due to their industry average 100,000 hour life cycle and five to ten year warranty.

Advantages

- Long lifespan due to the lack of electrodes - between 65,000 and 100,000 hours depending on the lamp model;
- Very high energy conversion efficiency of between 62 and 90 Lumens/Watt [higher wattage lamps are more energy efficient];
- High power factor due to the low loss of the high frequency electronic ballasts which are typically between 95% and 98% efficient;
- Minimal Lumen depreciation (declining light output with age) compared to other lamp types as filament evaporation and depletion is absent;
- “Instant-on” and hot re-strike, unlike most conventional lamps used in commercial/industrial lighting applications (such as Mercury-vapor lamp, Sodium-vapor lamp and Metal halide lamp);
- Environmentally friendly as induction lamps use less energy, and use less mercury per hour of operation than conventional lighting due to their long lifespan. The mercury is in a solid form and can be easily recovered if the lamp is broken, or for recycling at end-of-life.

These benefits offer a considerable cost savings of between 35% and 55% in energy and maintenance costs for induction lamps compared to other types of commercial and industrial lamps which they replace.

Chapter- 6

Neon Lamp

A general electric NE-34 glow lamp, manufactured circa 1930

A **neon lamp** (also **neon glow lamp**) is a miniature gas discharge lamp that typically contains neon gas at a low pressure in a glass capsule. Only a thin region adjacent to the electrodes glows in these lamps, which distinguishes them from the much longer and brighter neon tubes used for signage. The term "neon lamp" is generally extended to lamps with similar design that operate with different gases. Neon glow lamps were very common in the displays of electronic instruments through the 1970s; the basic design of neon lamps is now incorporated in contemporary plasma displays.

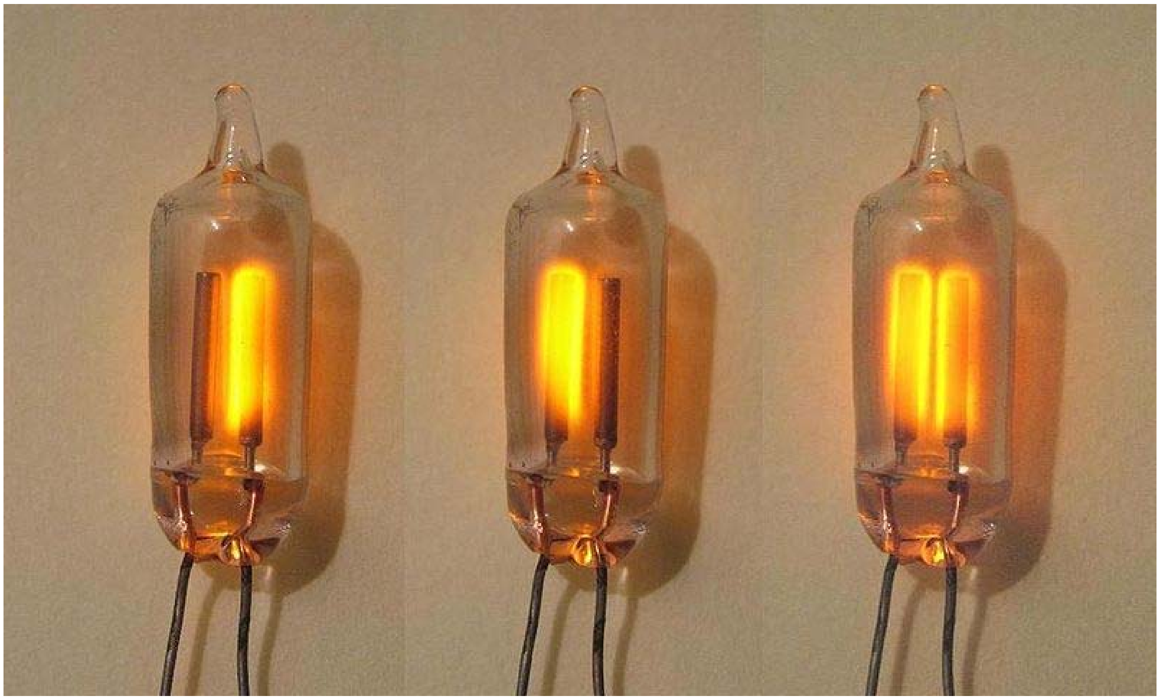
History

Neon was discovered in 1898 by William Ramsey and Morris W. Travers. The characteristic, brilliant red color that is emitted by gaseous neon when excited electrically was noted immediately; Travers later wrote, "the blaze of crimson light from the tube told its own story and was a sight to dwell upon and never forget."

Neon's scarcity precluded its prompt application for electrical lighting along the lines of Moore tubes, which used electric discharges in nitrogen and which were commercialized in the early 1900s. After 1902, Georges Claude's company, Air Liquide, was producing industrial quantities of neon as a byproduct of his air liquefaction business, and in December 1910 Claude demonstrated modern neon lighting based on a sealed tube of neon. In 1915 a U.S. patent was issued to Claude covering the design of the electrodes for neon tube lights; this patent became the basis for the monopoly held in the U.S. by his company, Claude Neon Lights, through the early 1930s.

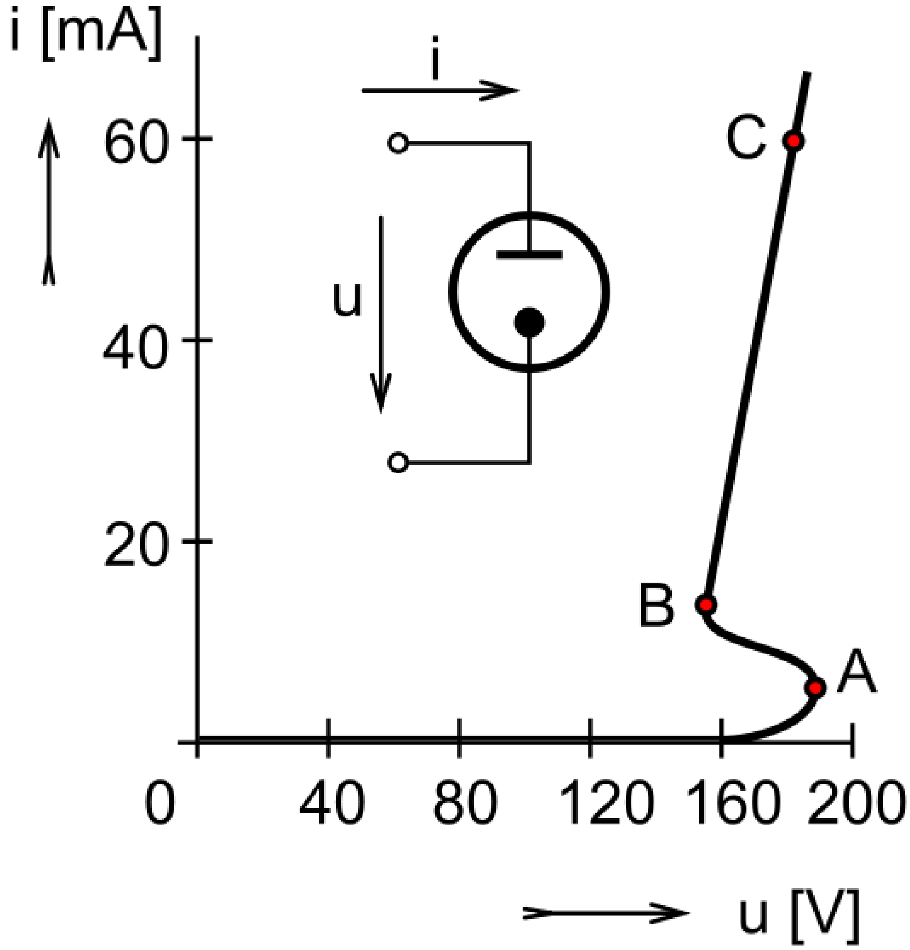
Around 1917, Daniel McFarlan Moore, then working at the General Electric Company, developed the neon lamp, which has a very different design than the much larger neon tubes used for neon lighting. The difference in design was sufficient that a U.S. patent was issued for the lamp in 1919. A Smithsonian Institution website notes, "These small, low power devices use a physical principle called coronal discharge. Moore mounted two electrodes close together in a bulb and added neon or argon gas. The electrodes would glow brightly in red or blue, depending on the gas, and the lamps lasted for years. Since the electrodes could take almost any shape imaginable, a popular application has been fanciful decorative lamps. Glow lamps found practical use as indicators in instrument panels and in many home appliances until the acceptance of Light-Emitting Diodes (LEDs) in the 1970s."

Description



DC and AC supplied neon lamps

A small electric current, which may be AC or DC, is allowed through the tube, causing it to glow orange-red. The exact formulation of the gas is typically the classic Penning mixture, 99.5% neon and 0.5% argon, which has lower striking voltage than pure neon. The applied voltage must initially reach the striking voltage before the lamp can light. Once lit, the voltage required to sustain operation is significantly (~30%) lower. When driven from a DC source, only the negatively charged electrode (cathode) will glow. When driven from an AC source, both electrodes will glow (each during alternate half cycles). These attributes make neon bulbs (with series resistors) very convenient as the basis for low-cost voltage testers; they determine whether a given voltage source is AC or DC, and if DC, the polarity of the points being tested. Neon lamps operate using a low current glow discharge. Higher power devices, such as mercury-vapor lamps or metal halide lamps use a higher current arc discharge.



Graph showing the "negative resistance" relationship between current and voltage across a neon lamp.

Once lit, a neon lamp has a negative resistance characteristic: increasing the current through the device increases the number of ions, thereby decreasing the resistance of the lamp and allowing even more current. (This behavior occurs between the points labeled A and B on the lamp's current vs. voltage graph.) Because of this characteristic, electrical circuitry external to the neon lamp must provide a means to limit current through the circuit or else the current will rapidly increase until the lamp is destroyed. For indicator-sized lamps, a resistor is conventionally used to limit the current. Larger neon sign sized lamps often use a specially constructed high voltage transformer or ballast to limit the available current, usually by introducing a large amount of leakage inductance in the secondary winding.

When the current through the lamp is lower than the current for the highest-current discharge path, the glow discharge may become unstable and not cover the entire surface of the electrodes. This may be a sign of aging of the indicator bulb, and is exploited in the decorative "flicker flame" neon lamps. However, while too low a current causes flickering, too high a current increases the wear of the electrodes by stimulating sputtering, which coats the internal surface of the lamp with metal and causes it to darken.

The flickering effect is caused by the differences of the ionization potential of the gas, which depends on spacing of the electrodes, temperature, ambient radiation, and the pressure of the gas. The potential needed to strike the discharge is higher than what is needed to sustain the discharge. When there is not enough current to ionize the entire volume of the gas around the electrodes, only partial ionization occurs and the glow forms around only part of the electrode surface. Convective currents make the glowing areas flow upwards, not unlike the discharge in a Jacob's ladder. A photoionization effect can also be observed here, as the electrode area covered with the discharge can be increased by shining light at the lamp.

In comparison with incandescent light bulbs, neon lamps have much higher luminous efficacy. Incandescence is heat-driven light emission, so a large portion of the electric energy put into an incandescent bulb is converted into heat. Non-incandescent light sources such as neon light bulbs, fluorescent light bulbs, and light emitting diodes are therefore much more energy efficient than normal incandescent light bulbs. Green neon bulbs can produce up to 65 lumens per watt of power input, while white neon bulbs have an efficacy of around 50 lumens per watt. In contrast, a standard incandescent light bulb only produces around 13.5 lumens per watt.

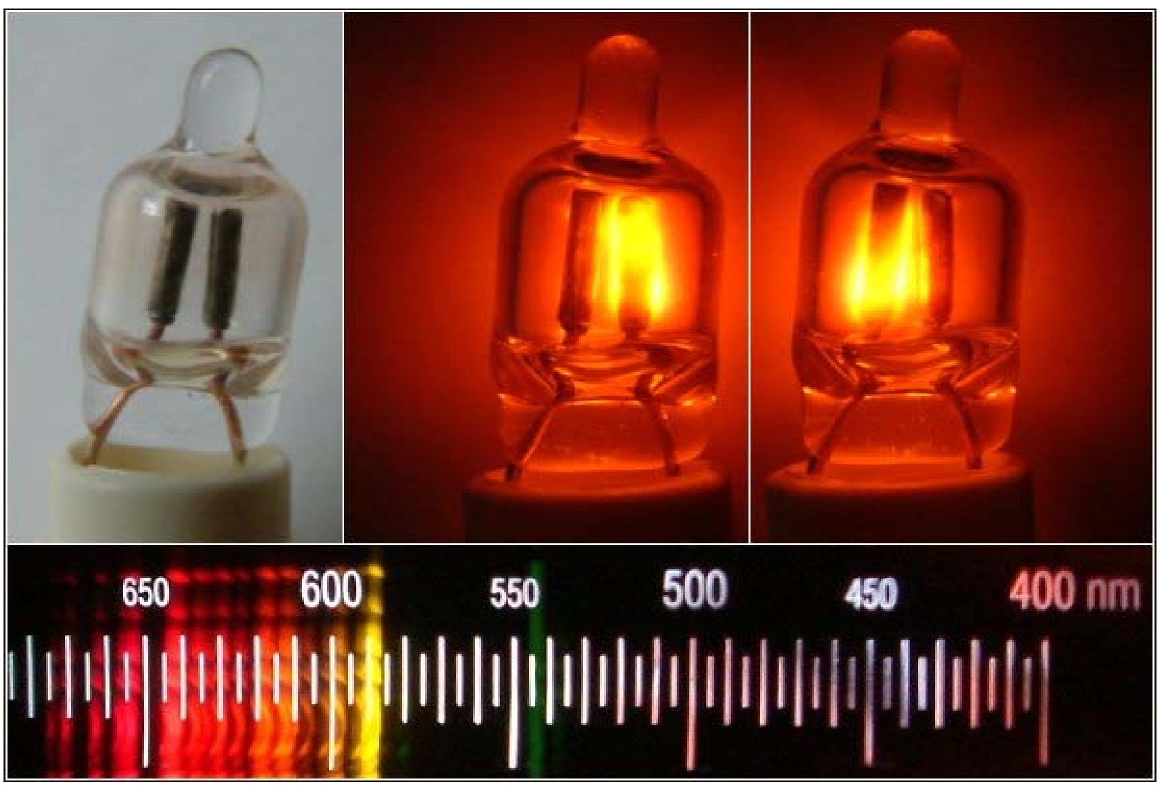
Applications

The digits of a Nixie tube.

Most small neon (indicator-sized) lamps, such as the common **NE-2**, break down at between 90 and 110 volts. This feature enables their use as very simple voltage regulators or overvoltage protection devices. In the 1960s General Electric (GE), Signalite, and other firms made special extra-stable neon lamps for electronic uses. They even devised digital logic circuits, binary memories, and frequency dividers using neon lamps. Such circuits appeared in electronic organs of the 1950s, as well as some instrumentation. At least some of these lamps had a glow concentrated into a small spot on the cathode, which made them unsuited to use as indicators. These were sometimes called "circuit-component" lamps, the other variety being indicators. A variant of the NE-2 type lamp, the NE-77, had three parallel wires (in a plane) instead of the usual two. It was also intended primarily to be a circuit component.

Small neon lamps are used as indicators in electronic equipment. Called "tuneons" in 1930s radio sets, they were fitted as tuning indicators, and would give a brighter glow as the station was tuned in correctly. Larger lamps are used in neon signage. Neon lamps, due to their low current consumption, are used as nightlights. Because of their comparatively fast response time, in the early development of television neon lamps were used as the light source in many mechanical-scan TV displays. They were also used for a variety of other purposes; since a neon lamp can act as a relaxation oscillator with an added resistor and capacitor, it can be used as a simple flashing lamp or audio oscillator.

Neon lamps with several shaped electrodes were used as alphanumerical displays known as Nixie tubes. These have since been replaced by other display devices such as light emitting diodes, vacuum fluorescent displays, and liquid crystal displays. Novelty glow lamps with shaped electrodes (such as flowers and leaves), often coated with phosphors, have been made for artistic purposes. In some of these, the glow that surrounds an electrode is part of the design.



Unlit and lit neon lamps (NE-2 type) and their light spectrum.

In AC-excited lamps, both electrodes produce light, but in a DC-excited lamp, only the negative electrode glows. Thus a neon lamp can be used to distinguish between AC and DC sources and to ascertain the polarity of DC sources.

Indicator-sized lamps can also be filled with argon, krypton, or xenon rather than neon, or mixed with it. While the electrical operating characteristics remain similar, the lamps light with a bluish glow (including some ultraviolet) rather than neon's characteristic reddish-orange glow. Ultraviolet radiation then can be used to excite a phosphor coating inside of the bulb and provide a wide range of various colors, including white. A mixture of neon and krypton can be used for green glow, but nevertheless "green neon" lamps are more commonly phosphor-based.

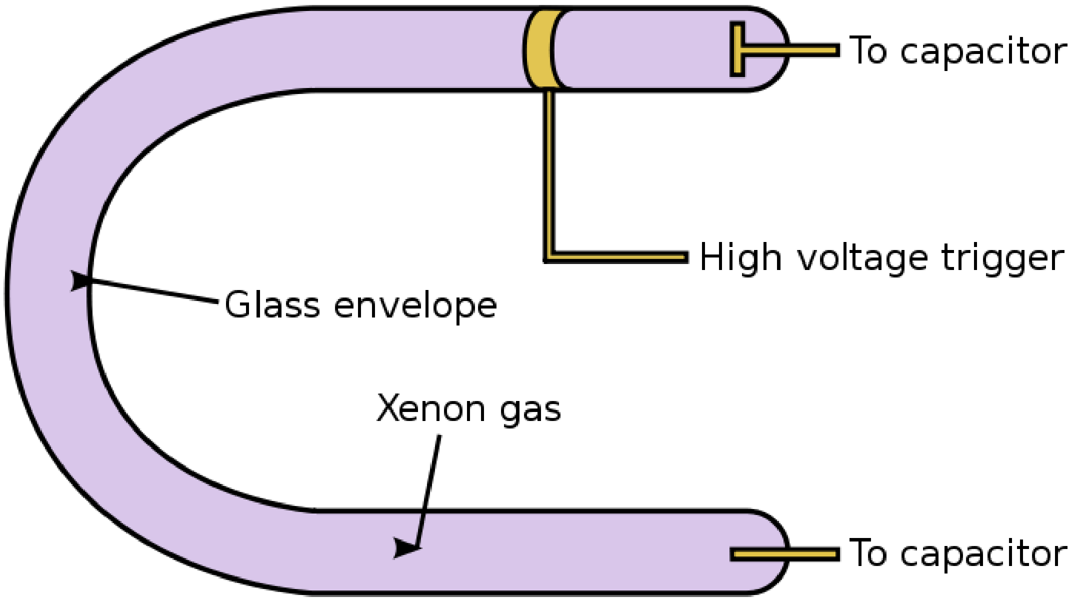
Chapter- 7

Flashtube

Helical xenon flashtube being fired

A **flashtube**, also called a **flashlamp**, is an electric glow discharge lamp designed to produce extremely intense, incoherent, full-spectrum white light for very short durations. Flashtubes are made of a length of glass tubing with electrodes at either end and are filled with a gas that, when triggered, ionizes and conducts a high voltage pulse to produce the light. Flashtubes are used mostly for photographic purposes but are also employed in scientific, medical and industrial applications.

Construction

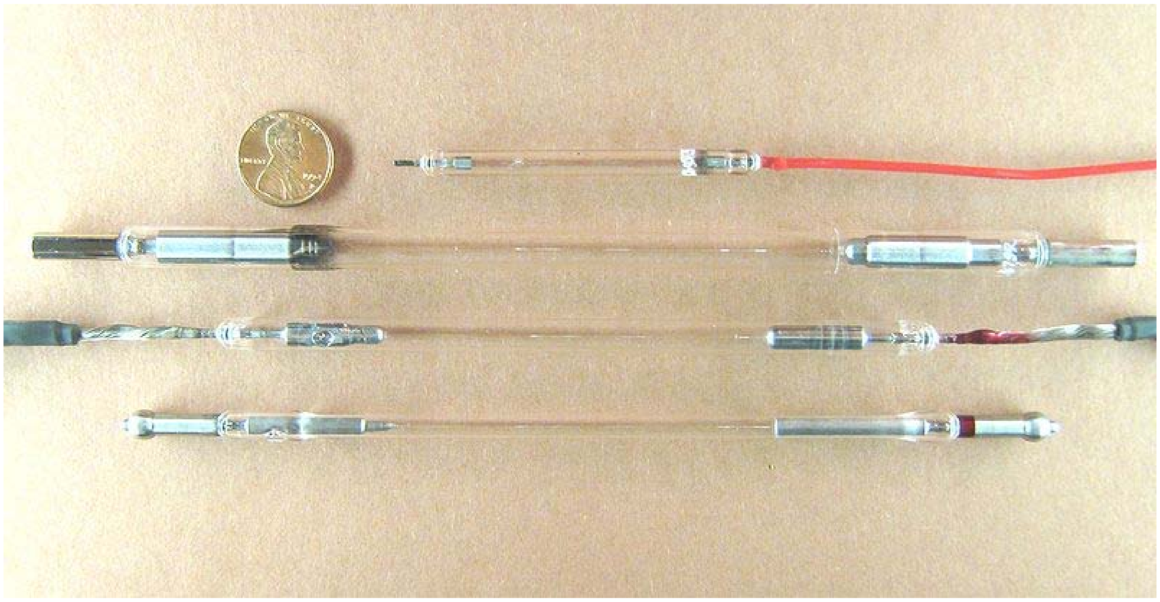


U-shaped xenon flashtube

The lamp comprises a hermetically sealed glass tube, which is filled with a noble gas, usually xenon, and electrodes to carry electrical current to the gas. Additionally, a high voltage power source is necessary to energize the gas. A charged capacitor is usually used for this purpose so as to allow very speedy delivery of very high electrical current when the lamp is triggered.

The glass envelope is most commonly a thin tube, often made of fused quartz, borosilicate or Pyrex, which may be straight, or bent into a number of different shapes, including helical, "U" shape, and circular (to surround a camera lens for shadowless photography—'ring flashes'). In some applications the emission of ultraviolet light is undesired, whether due to production of ozone, damage to laser rods, degradation of plastics, or other detrimental effects. In these cases a doped fused silica is used. Doping with titanium dioxide can provide different cutoff wavelengths on the ultraviolet side, but the material suffers from solarization; it is often used in medical and sun-ray lamps and some non-laser lamps. A better alternative is a cerium-doped quartz; it does not suffer from solarization and has higher efficiency, as part of the absorbed ultraviolet is reradiated as visible via fluorescence. Its cutoff is at about 380 nm. Conversely, when ultraviolet is called for, a synthetic quartz is used as the envelope; it is the most expensive of the materials, but it is not susceptible to solarization and its cutoff is at 160 nm.

The electrodes protrude into each end of the tube, and are sealed to the glass using a few different methods. "Ribbon seals" use thin strips of molybdenum foil bonded directly to the glass, which are very durable, but are limited in the amount of current that can pass through. "Solder seals" bond the glass to the electrode with a solder for a very strong mechanical seal, but are limited to low temperature operation. Most common in laser pumping applications is the "rod seal", where the rod of the electrode is wetted with another type of glass and then bonded directly to a quartz tube. This seal is very durable and capable of withstanding very high temperature and currents.



Flashtubes of various sizes for laser pumping. The top three are xenon flashtubes. The last one is a krypton arc lamp, (shown for comparison).

For low electrode wear the electrodes are usually made of tungsten, which has the highest melting point of any metal, to handle the thermionic emission of electrons. Cathodes are often made from porous tungsten filled with a barium compound, which gives low work function; the structure of cathode has to be tailored for the application. Anodes are usually made from pure tungsten, or, when good machinability is required, lanthanum-alloyed tungsten, and are often machined to provide extra surface area to cope with power loading. DC arc lamps often have a cathode with a sharp tip, to help keep the arc away from the glass and to control temperature. Flashtubes usually have a cathode with a flattened radius, to reduce the incidence of hot spots and decrease sputter caused by peak currents, which may be in excess of 1000 amperes. Electrode design is also influenced by the average power. At high levels of average power, care has to be taken to achieve sufficient cooling of the electrodes. While anode temperature is of lower importance, overheating the cathode can greatly reduce the lamp's lifetime.

The power level of the lamps is rated in watts/area, total output power divided by the lamp's surface. Cooling of the electrodes and the lamp envelope is of high importance at high power levels. Air cooling is sufficient for lower average power levels. High power lamps are cooled with a liquid, typically by flowing demineralized water through a tube in which the lamp is encased. The cooling medium should flow also over the ends of the lamps, seals and electrodes. Above 15 W/cm^2 forced air cooling is required, liquid cooling if in a confined space. Liquid cooling is generally necessary above 30 W/cm^2. Thinner walls can survive higher power loads due to lower mechanical strain across the thickness of the material; e.g. 1mm thick doped quartz has limit of 160 W/cm^2, 0.5mm thick one has limit of 320 W/cm^2. The material of the envelope provides another limit for the output power; 1mm thick fused quartz has a limit of 200 W/cm^2, synthetic quartz of same thickness can run up to 240 W/cm^2. Aging lamps require some derating, due to increased energy absorption in the glass due to solarization and sputtered deposits.

Depending on the size, type, and application of the flashtube, gas fill pressures may range from a few kilopascals to hundreds of kilopascals (0.01–4.0 atmospheres or tens to thousands of torr). Generally, the higher the pressure, the greater the output efficiency. Xenon is used mostly because of its good efficiency, converting nearly 50% of electrical energy into light. Krypton, on the other hand, is only about 40% efficient, but at low currents is a better match to the absorption spectrum of Nd:YAG lasers. A major factor affecting efficiency is the amount of gas behind the electrodes, or the "dead volume". A higher dead volume leads to a lower pressure increase during operation.

Operation

The electrodes of the lamp are usually connected to a capacitor, which is charged to a relatively high voltage (generally between 250 and 5000 volts), using a step up transformer and a rectifier. The gas, however, exhibits extremely high resistance, and the lamp will not conduct electricity until the gas is ionized. Once ionized, or "triggered", a spark will form between the electrodes, allowing the capacitor to discharge. The sudden surge of electric current quickly heats the gas to a plasma state, where electrical resistance becomes very low. There are several methods of triggering.

External triggering

External triggering is the most common method of operation, especially for photographic use. The electrodes are charged to a voltage high enough to respond to triggering, but below the lamp's self-flash threshold. An extremely high voltage pulse, (usually between 2000 and 150,000 volts), the "trigger pulse", is applied directly to, or very near, the glass envelope. (Water cooled flashtubes sometimes apply this pulse directly to the cooling water, and often to the housing of the unit as well, so care must be taken with this type of system.) The short, high voltage pulse creates a rising electrostatic field, which ionizes the gas inside the tube. The capacitance of the glass couples the trigger pulse into the envelope, where it exceeds the breakdown voltage of the gas surrounding one or both of the electrodes, forming spark streamers. The streamers propagate via capacitance along the glass at a speed of 1 centimeter in 60 nanoseconds (=170 km/s) . (A trigger pulse must have a long enough duration to allow one streamer to reach the opposite electrode, or erratic triggering will result.) The triggering can be enhanced by applying the trigger pulse to a "reference plane", which may be in the form of a metal band or reflector affixed to the glass, a conductive paint, or a thin wire wrapped around the length of the lamp. When the internal spark streamers bridge the electrodes, the capacitor discharges through the ionized gas, heating the xenon to a high enough temperature for the emission light.

Series triggering

Series triggering is more common in high powered, water cooled flashtubes, such as those found in lasers. The high voltage leads of the trigger-transformer are connected to the flashtube in series, (one lead to an electrode and the other to the capacitor). The trigger pulse forms a spark inside the lamp, without exposing the trigger voltage to the outside of the lamp. The advantages are better insulation, more reliable triggering, and an arc that tends to develop well away from the glass, but at a much higher cost.

Simmer voltage triggering

A 3.5 microsecond flash, using external triggering

Simmer voltage triggering is the least common method. In this technique, the capacitor voltage is not initially applied to the electrodes, but instead, a high voltage spark streamer is maintained between the electrodes. The high current from the capacitor is delivered to the electrodes using a thyristor or a spark gap. This type of triggering is used mainly in very fast rise time systems, typically those that discharge in the microsecond regime, such as used in high speed stop-motion photography, or dye lasers. If external triggering is used, the spark streamers may still be in contact with the glass when the full current load passes through the tube, causing wall ablation, or in extreme cases, cracking or even explosion of the lamp. Some microsecond flashtubes are triggered by simply "overvolting", that is, by applying a voltage to the electrodes which is much higher than the lamp's self-flash threshold, using a spark gap.

Variable pulse width control

In addition, an insulated-gate bipolar transistor (IGBT) can be connected in series with both the trigger transformer and the lamp, making adjustable flash durations possible. An IGBT used for this purpose must be rated for a high pulsed current, so as to avoid over-current damage to the semiconductor junction. This type of system is used frequently in high average power laser systems, and can produce pulses ranging from 500 microseconds to over 20 milliseconds. It can be used with any of the triggering techniques, like external and series, and can produce square wave pulses. It can even be used with simmer voltage to produce a "modulated" continuous wave output, with repetition rates over 300 hertz. With the proper large bore, water cooled flashtube, several kilowatts of average power output can be obtained.

Electrical requirements

The electrical requirements for a flashtube can vary, depending on the desired results. The usual method, once maximum power and the safe amount of operating energy is determined, is to pick a current density that will emit the desired spectrum, and let the lamp's resistance determine the necessary combination of voltage and capacitance to produce it. The resistance in flashtubes varies greatly, depending on pressure, shape, dead volume, current density, time, and flash duration, and therefore, is usually referred to as impedance. The most common symbol used for lamp impedance is $\mathbf{K_o}$, which is expressed as ohms(amps$^{0.5}$).

Output spectrum

Xenon

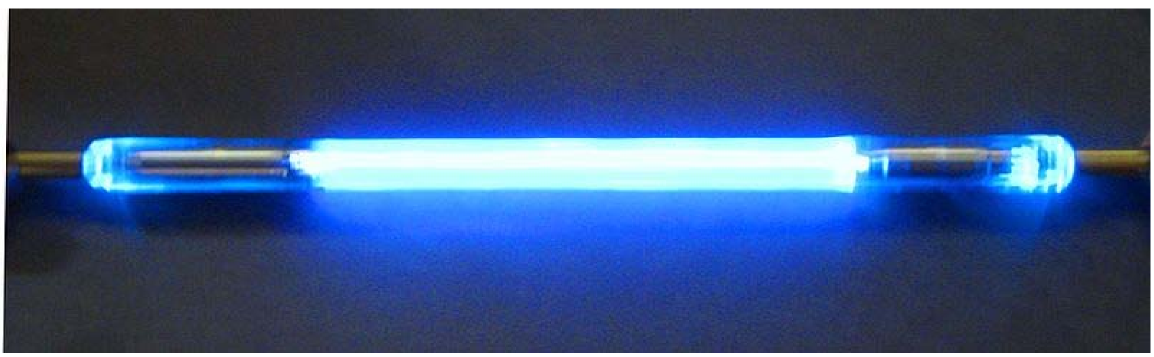
Xenon, operated as a 'neon light'

As with all ionized gases, xenon flashtubes emit light in various spectral lines. This is the same phenomenon that gives neon signs their characteristic color. However, neon signs emit red light because of extremely low current densities when compared to those seen in flashtubes, which favors spectral lines of longer wavelengths . Higher current densities tend to favor shorter wavelengths. The light from xenon, in a neon sign, likewise is rather violet.

The spectrum emitted by flashtubes is far more dependent on current density than on the fill pressure or gas type. Low current densities produce spectral line emission, against a faint background of continuous radiation. Xenon has many spectral lines in the UV, blue, green, red, and IR portions of the spectrum. Low current densities produce a greenish-blue flash, indicating the absence of significant yellow or orange lines. At low current densities, most of xenon's output will be directed into the invisible IR spectral lines around 820, 900, and 1000 nm. Low current densities for flashtubes are generally less than 1000 A/cm^2.

Higher current densities begin to produce continuum emission. Spectral lines are less dominant as light is produced across the spectrum, usually peaking, or "centered", on a certain wavelength. Optimum output efficiency in the visual range is obtained at a density that favors "greybody radiation" (an arc that produces mostly continuum emission, but is still mostly transparent to its own light). For xenon, greybody radiation is centered near green, and produces the right combination for white light. Greybody radiation is produced at densities above 2400 A/cm^2.

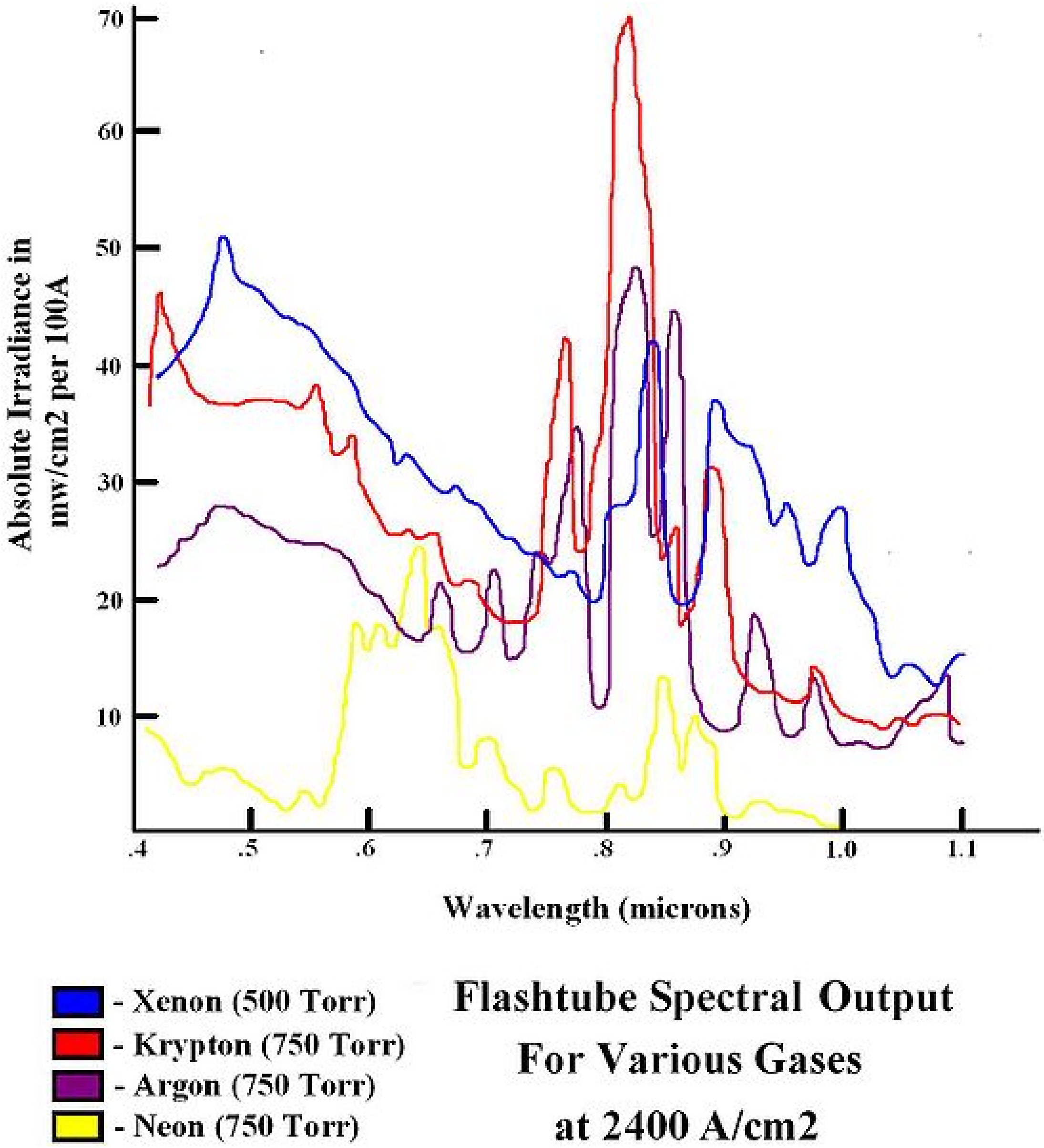
Current densities that are very high, approaching 4000 A/cm^2, tend to favor blackbody radiation. As current densities become even higher, xenon's output spectrum will begin to settle on that of a blackbody radiator with a color temperature of 9800 kelvins (a rather sky-blue shade of white). Blackbody radiation is usually not desired, because much of the radiation from within the arc can be absorbed before reaching the surface, impairing output efficiency.



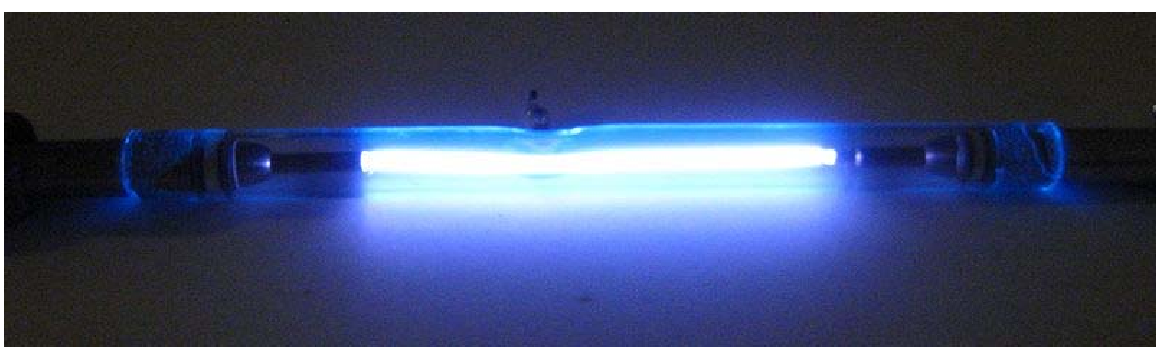
Spectral line radiation from a xenon flashlamp.

Due to its high efficient white output, xenon is used extensively for photographic applications, despite its great expense. In lasers, spectral line emission is usually favored, as these lines tend to better match absorption lines of the lasing media. Krypton is also occasionally used, although it is even more expensive. At low current densities, krypton's spectral line output in the near-IR range is better matched to the absorption profile of neodymium based laser media than xenon emission, and very closely matches the narrow absorption profile of Nd:YAG.

Krypton and other gases



Spectral outputs of various gases.



Argon flashlamp spectral line radiation.

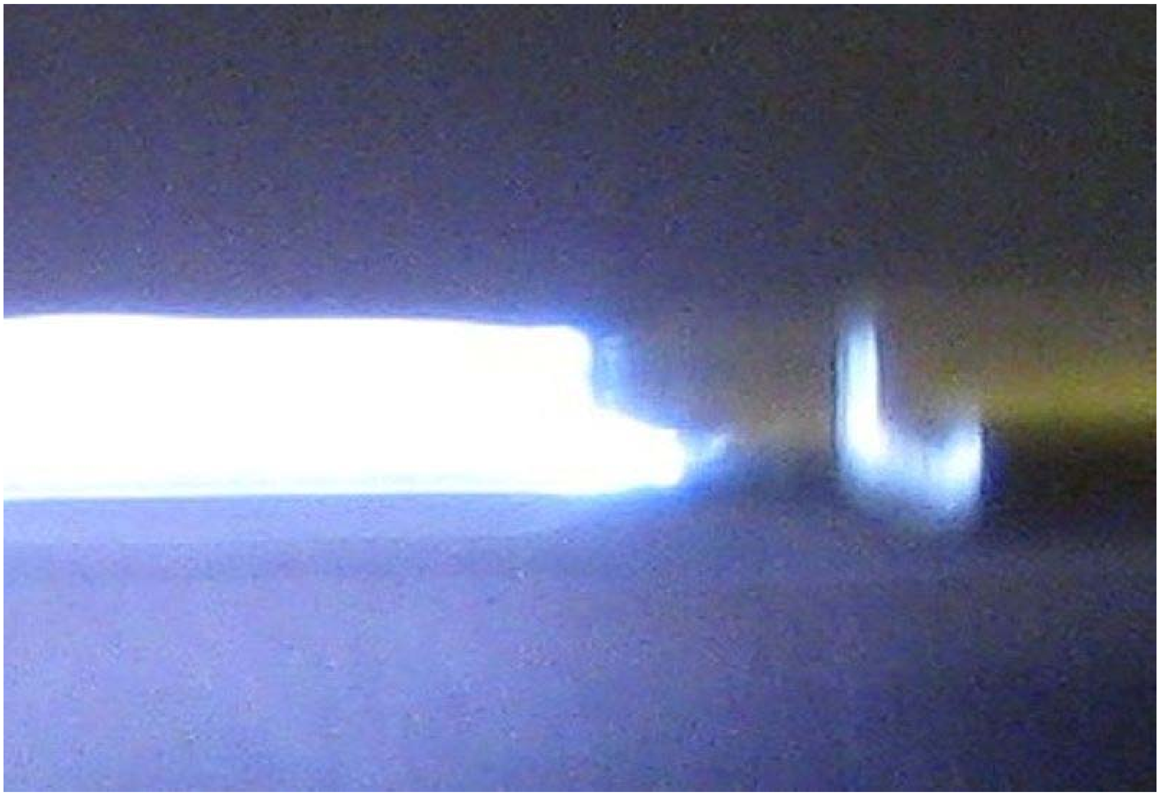
An extensive study was done in the 1960s on the characteristics of other gases when operated in flashtubes. All gases produce spectral lines which are specific to the gas, superimposed on a background of continuum radiation. Like xenon, low current densities produce mostly spectral lines, with the highest output being concentrated in the near-IR between 650 and 1000 nm. Krypton's strongest peaks are around 760 and 810 nm. Argon has many strong peaks at 670, 710, 760, 820, 860, and 920 nm. Neon has peaks around 650, 700, 850, and 880 nm. As current densities become higher, the output of continuum radiation will increase more than the spectral line radiation at a rate 20% greater, and output center will shift toward the visual spectrum. At greybody current densities there is only a slight difference in the spectrum emitted by various gases. At very high current densities, all gases will begin to operate as blackbody radiators, with spectral outputs centered in the near-UV.

Heavier gases exhibit higher resistance, and therefore, have a higher value for $\mathbf{K_0}$. Impedance, being defined as the resistance required to change energy into work, is higher for heavier gases, and as such, the heavier gases are much more efficient than the lighter ones. Helium and neon are far too light to produce an efficient flash. Krypton can be as good as 40% efficient, but requires up to a 70% increase in pressure to achieve this. Argon can be up to 30% efficient, but requires an even greater pressure increase. At such high pressures, the voltage drop between the electrodes, formed by the spark streamer, may be greater than the capacitor voltage. These lamps often need a "boost voltage" during the trigger phase, to overcome the extremely high trigger impedance.

Nitrogen, in the form of air, has been used in flashtubes in home made dye lasers, but the nitrogen and oxygen present form chemical reactions with the electrodes, and themselves, causing premature wear and the need to adjust the pressure for each flash.

Some research has been done on mixing gases to alter the spectral output. The effect on the output spectrum is negligible, but the effect on efficiency is great. Adding a lighter gas will only reduce the efficiency of the heavier one.

Light production

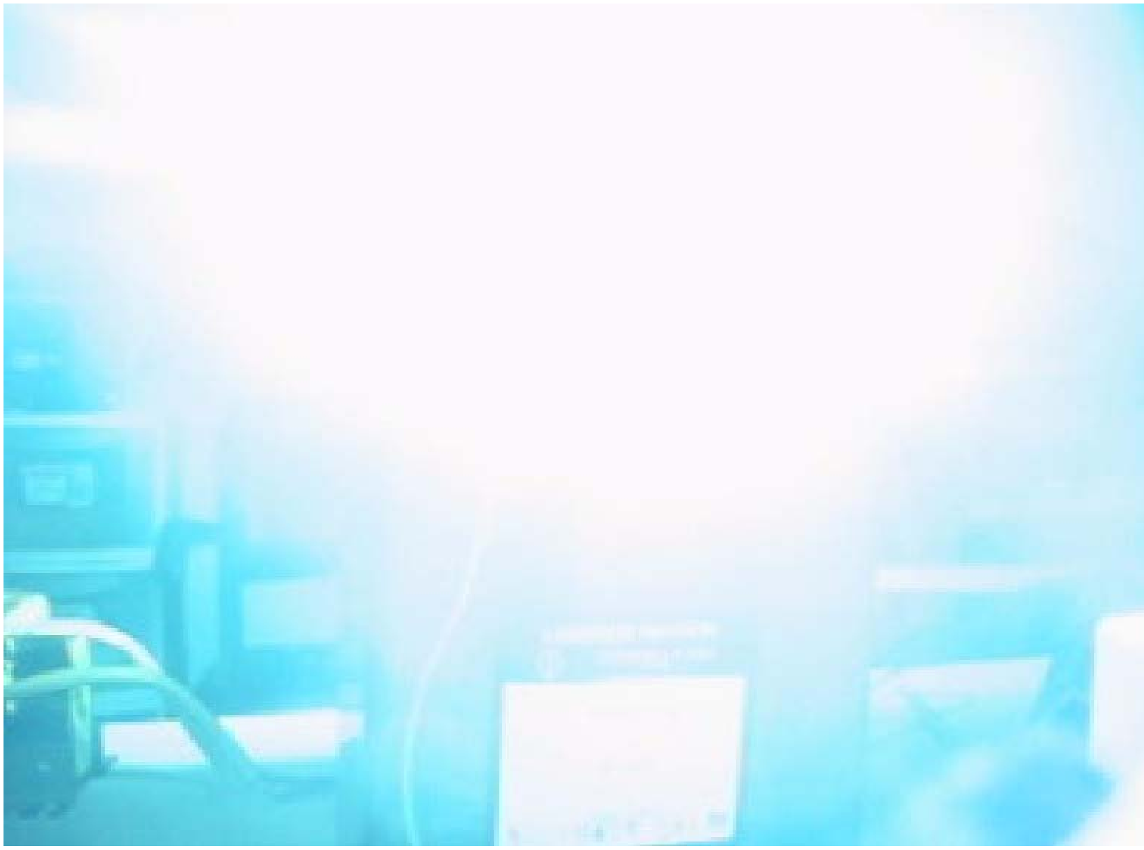


Krypton arc plasma

As the current pulse travels through the tube, it ionizes the atoms, causing them to jump to higher energy levels. Three types of particles are found within the arc plasma, consisting of electrons, positively ionized atoms, and neutral atoms. At any given time, the ionized atoms make up less than 1% of the plasma and produce all of the emitted light. As they recombine with their lost electrons they immediately drop back to a lower energy state, releasing photons in the process. The methods of transferring energy occur in three separate ways, called "bound-bound," "free-bound," and "free-free" transitions.

Within the plasma, positive ions move toward the cathode while electrons and neutral atoms move toward the anode. Bound-bound transitions occur when the ions and neutral atoms collide, transferring an electron from the atom to the ion. This method predominates at low current densities, and is responsible for producing the spectral line emission. Free-bound transitions happen when an ion captures a free electron. This method produces the continuum emission, and is more prominent at higher current densities. Some of the continuum is also produced when an electron accelerates toward an ion, called free-free transitions, producing bremsstrahlung radiation.

Intensity and duration of flash



An 85 joule, 3.5 microsecond flash. While the energy level is moderately low, electrical power at such a short duration is 24 million watts. The blackbody radiation is so intense that it has no problem penetrating the extremely dark, shade 10 welding lens which the camera is behind.

For short pulses the only real electrical limit is the total system inductance, including that of the capacitor. Short pulse flashes require that all inductance be minimized. The amount of power loading the glass can handle is the major mechanical limit. Although the amount of energy, or joules, that is used remains constant, electrical power, or wattage, increases in inverse proportion to a decrease in discharge time. Quartz glass, 1 millimeter thick, can usually withstand a maximum of 160 watts per square centimeter of internal surface area. Other glasses have a much lower threshold. Extremely fast systems, with inductance below 0.8 microhenries, usually require a shunt diode across the capacitor, to prevent current reversal from destroying the lamp.

The limits to long pulse durations are the number of transferred electrons to the anode, sputter caused by ion bombardment at the cathode, and the temperature gradients of the glass. For continuous operation the cooling is the limit. Discharge durations for common flashtubes range from 1 microsecond to tens of milliseconds, and can have repetition rates of hundreds of hertz. Flash duration can be carefully controlled with the use of an inductor.

The flash that emanates from a xenon flashtube may be so intense that it can ignite flammable materials within a short distance of the tube. Carbon nanotubes are particularly susceptible to this spontaneous ignition when exposed to the light from a flashtube. Similar effects may be exploited for use in aesthetic or medical procedures known as intense pulsed light (IPL) treatments. IPL can be used for treatments such as hair removal and destroying lesions or moles.

Lifetime

The lifetime of a flashtube depends on both the energy level used for the lamp in proportion to its explosion energy, and on the pulse duration of the lamp. Failures can be catastrophic, causing the lamp to shatter, or they can be gradual, reducing the performance of the lamp below a usable rating.

Catastrophic failure

Catastrophic failure can occur from two separate mechanisms; energy and heat. When too much energy is used for the pulse duration, structural failure of the glass envelope can occur. Flashtubes produce an electrical arc contained in a glass tube. As the arc develops a supersonic shock wave forms, traveling radially from the center of the lamp and impacting the inner wall of the tube. If the energy level used equals the "explosion energy" rating of the lamp, the impacting shockwave will fracture the glass, rupturing the tube. The resulting explosion creates a loud sonic shock wave, and may throw shattered glass several feet. The explosion energy is calculated by multiplying the internal surface area of the lamp with the power loading capacity of the glass. Power loading is determined by the type and thickness of the glass, and measured in watts per centimeter squared. Since the pulsed power level increases as the flash duration decreases, the explosion energy is adjusted in direct proportion to the square root of discharge time.

Failure from heat is usually caused by excessively long pulse durations or high average power levels. When the inner wall of the tube gets too hot while the outer wall is still cold, this temperature gradient can cause the lamp to crack. Similarly, if the electrodes heat much faster than the glass, the lamp may crack or even shatter at the ends.

Gradual failure

Flashtube cathodes, showing early signs of wear. The tube on the left shows sputter, while the tube on the right shows wall ablation.

The closer a flashtube operates to its explosion energy, the greater the risk becomes for catastrophic failure. At 50% of the explosion energy, the lamp may produce several thousand flashes before exploding. At 60% of the explosion energy, the lamp will usually fail in less than a hundred. If the lamp is operated below 30% of the explosion energy the risk of catastrophic failure becomes very low. The methods of failure then become those that reduce the output efficiency and affect the ability to trigger the lamp. The processes affecting these are sputter and ablation of the inner wall.

Sputter occurs when the energy level is very low, below 15% of the explosion energy, or when the pulse duration is very long. Sputter is the vaporization of metal from the cathode, which is redeposited on the walls of the lamp, blocking the light output. Since the cathode is more emissive than the anode, the flashtube is polarized, and connecting the lamp to the power source incorrectly will quickly ruin it. It is impossible to predict the lifetime accurately at low energy levels.

At higher energy levels, wall ablation becomes the main process of wear. The electrical arc slowly erodes the inner wall of the tube, forming microscopic cracks that give the glass a frosted appearance. The ablation releases oxygen from the glass, increasing the pressure beyond an operable level. This causes triggering problems, known as "jitter". However, at higher energy levels the lifetime can be calculated with a fair degree of accuracy.

Applications

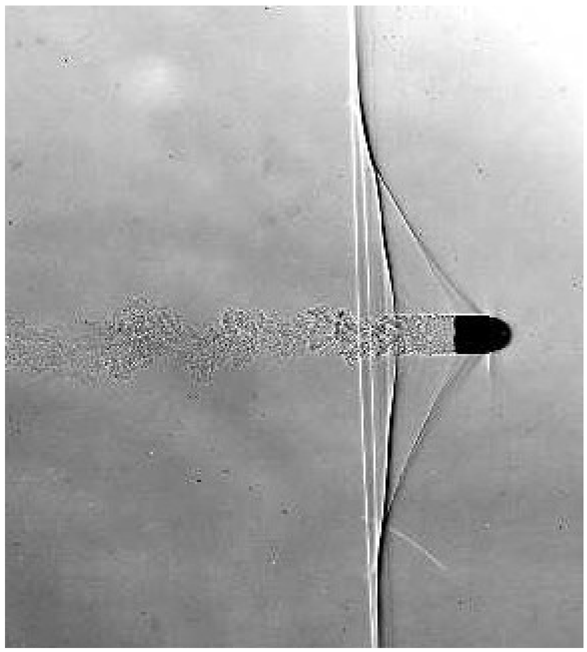
The 6 foot (180 cm) flashtubes used on the National Ignition Facility laser are the largest ever in commercial production, operating at 30 kJ input power per pulse.

Because the duration of the flash that is emitted by a xenon flashtube can be accurately controlled, and due to the high intensity of the light, xenon flashtubes are commonly used as photographic strobe lights. Xenon flashtubes are also used in the technique of very high speed or "stop-motion" photography, which was pioneered by Harold Edgerton in the 1930s. Because they can generate bright, attention-getting flashes with a relatively small continuous input of electrical power, they are also used in warning lights, emergency vehicle lighting, fire alarm annunciator devices (*horn lights*), aircraft anticollision beacons, and other similar applications.

Due to their high-intensity and relative brightness at short wavelengths (extending into the ultraviolet) and short pulse widths, flashtubes are also ideally suited as light sources for pumping atoms in a laser to excited states where they can subsequently be stimulated to emit coherent monochromatic light. Proper selection of the filler gas is crucial here, so the maximum of radiated output energy is concentrated in the bands that are the best absorbed by the lasing medium; e.g. krypton flashtubes are more suitable than xenon flashtubes for pumping Nd:YAG lasers, as krypton emission in near infrared is better matched to the absorption spectrum of Nd:YAG.

Xenon flashtubes have been used to produce an intense flash of white light, some of which is absorbed by Nd:glass that produces the laser power for inertial confinement fusion. In total about 1 to 1.5% of the electrical power fed into the flashtubes is turned into useful laser light for this application.

History



This shadowgraph of a bullet in supersonic flight was taken using a discharge from a high-speed flashtube.

The flashtube was invented by Harold Edgerton in the 1930s as a means to take sharp photographs of moving objects. Flashtubes were mainly used for strobe lights in scientific studies, but eventually began to take the place of chemical and powder flash lamps in mainstream photography.

Early high-speed photographs were taken with an open-air electrical arc discharge, called spark photography. The earliest known use of spark photography began with Henry Fox Talbot around 1850. In 1886, Ernst Mach used an open air spark to photograph a speeding bullet, revealing the shockwaves it produced at supersonic speeds. Open air spark systems were fairly easy to build, but were bulky, very limited in light output, and produced loud noises comparable to that of the gunshot.

In 1927, Harold Edgerton built his first flash unit while at MIT. Wanting to photograph the motion of a motor in vivid detail, without blur, Edgerton decided to improve the process of spark photography by using a mercury-arc rectifier instead of an open air discharge to produce the light. He was able to achieve a flash duration of 10 microseconds, and was able to photograph the moving motor as if "frozen in time."

Interest in the new flash apparatus soon provoked Edgerton to improve upon the design. The mercury lamps were only as efficient as the warmest part of the lamp, causing them to perform better when very hot but poorly when cold. Edgerton decided that a noble gas would not be as temperature dependent, and began building lamps using argon instead. The argon lamps were much more efficient, compact, and could be mounted near a reflector, concentrating their output. Slowly, camera designers began to take notice of the new technology and began to accept it. Edgerton received his first major order for the strobes from the Kodak company in 1940. Afterward, he discovered that xenon was the most efficient of the noble gases, producing a spectrum very close to that of daylight, and xenon flashtubes became standard in most large photography sets. It was not until the 1970s that strobe units became portable enough to use in common cameras.

In 1960, after Theodore Maiman invented the ruby laser, a new demand for flashtubes began for use in lasers, and new interest was taken in the study of the lamps.

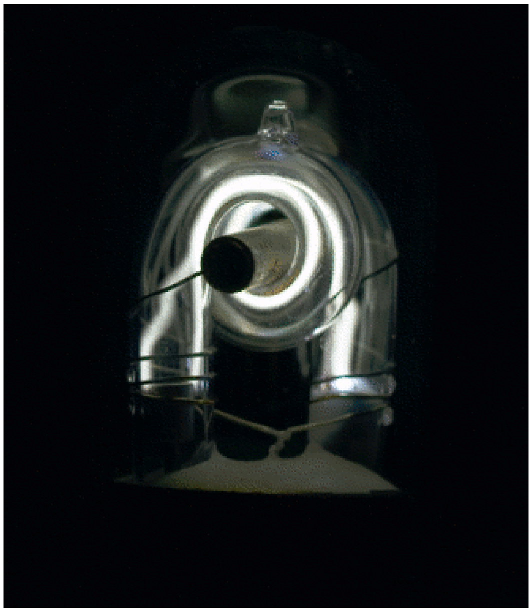
Safety

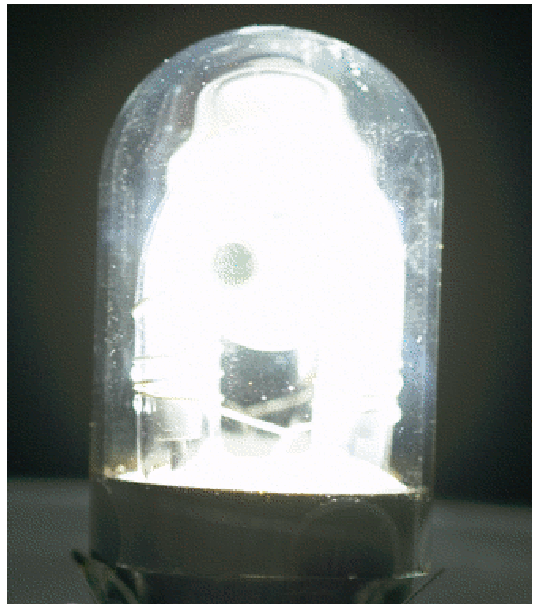
Flashtubes operate at high voltages, with currents high enough to be deadly. Shocks as low as 1 joule have been reported to be lethal. The energy stored in a capacitor can remain surprisingly long after power has been disconnected. A flashtube will usually shut down before the capacitor has fully drained, and it may regain part of its charge through a process called "dielectric absorption". In addition, the charging system itself can be equally deadly. The trigger voltage can deliver a painful shock, usually not enough to kill, but which can often startle a person into bumping to or touching something more dangerous. At high voltages a spark can jump, delivering the high capacitor current without even touching anything.

Flashtubes operate at high pressures and are known to explode, producing violent shockwaves. The "explosion energy" of a flashtube (the amount of energy that will destroy it in just a few flashes) is well defined, and to avoid catastrophic failure, it is recommended that no more than 30% of the explosion energy be used. Flashtubes should be shielded behind glass or in a reflector cavity. If not, eye and ear protection should be worn.

Flashtubes produce very intense flashes, often faster than the eye can register, and may not appear as bright as they are. Quartz glass will transmit nearly all of the long and short wave UV, including the germicidal wavelengths, and can be a serious hazard to eyes and skin. This ultraviolet radiation can also produce large amounts of ozone, which can be harmful to people, animals, and equipment.

Many compact cameras charge the flash capacitor immediately after power-up, and some even just by inserting the batteries. Merely inserting the battery into the camera can prime the capacitor to become dangerous or at least unpleasant for up to several days. The energy involved is also fairly significant; a 330 microfarad capacitor charged to 300 volts (common ballpark values found in cameras) stores almost 15 joules of energy.





Helical xenon flashtube being fired