Electric Powered Light Sources and Applications

(Artificial Light)

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First Edition, 2012

ISBN 978-81-323-2743-1

Published by:
Orange Apple
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
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Incandescent Light Bulb

An incandescent light bulb

The **incandescent light bulb**, **incandescent lamp** or **incandescent light globe** makes light by heating a metal filament wire to a high temperature until it glows. The hot filament is protected from air by a glass bulb that is filled with inert gas or evacuated. In a halogen lamp, a chemical process that returns metal to the filament prevents its evaporation. The light bulb is supplied with electrical current by feed-through terminals or wires embedded in the glass. Most bulbs are used in a socket (a housing giving mechanical support to the bulb, keeping its terminals in contact with the supply current terminals).

Incandescent bulbs are produced in a wide range of sizes, light output, and voltage ratings, from 1.5 volts to about 300 volts. They require no external regulating equipment and have a low manufacturing cost and work equally well on either alternating current or direct current. As a result, the incandescent lamp is widely used in household and commercial lighting, for portable lighting such as table lamps, car headlamps, and flashlights, and for decorative and advertising lighting.

Some applications of the incandescent bulb use the heat generated by the filament, such as incubators, brooding boxes for poultry, heat lights for reptile tanks, infrared heating for industrial heating and drying processes, and the Easy-Bake Oven toy. In cold weather, the heat produced by incandescent lamps is a benefit as it contributes to building heating, but in hot climates this waste heat increases the energy required by air conditioning systems.

Incandescent light bulbs are gradually being replaced in many applications by other types of electric lights, such as fluorescent lamps, compact fluorescent lamps, cold cathode fluorescent lamps (CCFL), high-intensity discharge lamps, and light-emitting diodes (LEDs). These newer technologies improve the ratio of visible light to heat generation. Some jurisdictions, such as the European Union, are in the process of phasing out the use of incandescent light bulbs in favor of more energy-efficient lighting. In the United States, federal law has scheduled incandescent light bulbs to be phased out by 2014, to be replaced with more energy-efficient light bulbs. In Brazil, they have already been phased out.

History of the light bulb

Original carbon-filament bulb from Thomas Edison.

In addressing the question of who invented the incandescent lamp, historians Robert Friedel and Paul Israel list 22 inventors of incandescent lamps prior to Joseph Swan and Thomas Edison. They conclude that Edison's version was able to outstrip the others because of a combination of three factors: an effective incandescent material, a higher vacuum than others were able to achieve (by use of the Sprengel pump) and a high resistance that made power distribution from a centralized source economically viable.

Another historian, Thomas Hughes, has attributed Edison's success to the fact that he developed an entire, integrated system of electric lighting.

The lamp was a small component in his system of electric lighting, and no more critical to its effective functioning than the Edison Jumbo generator, the Edison main and feeder, and the parallel-distribution system. Other inventors with generators and incandescent lamps, and with comparable ingenuity and excellence, have long been forgotten because their creators did not preside over their introduction in a system of lighting.

Historian Thomas P. Hughes

Early evolution of the light bulb

Early pre-commercial research

In 1802, Humphry Davy had what was then the most powerful electrical battery in the world at the Royal Institution of Great Britain. In that year, he created the first incandescent light by passing the current through a thin strip of platinum, chosen because the metal had an extremely high melting point. It was not bright enough nor did it last long enough to be practical, but it was the precedent behind the efforts of scores of experimenters over the next 75 years. In 1809, Davy also created the first arc lamp with two carbon charcoal rods connected to a 2000-cell battery; it was demonstrated to the Royal Institution in 1810.

Over the first three-quarters of the 19th century many experimenters worked with various combinations of platinum or iridium wires, carbon rods, and evacuated or semi-evacuated enclosures. Many of these devices were demonstrated and some were patented.

In 1835, James Bowman Lindsay demonstrated a constant electric light at a public meeting in Dundee, Scotland. He stated that he could "read a book at a distance of one and a half feet". However, having perfected the device to his own satisfaction, he turned to the problem of wireless telegraphy and did not develop the electric light any further. His claims are not well documented, although he is credited in Challoner etal. with being the inventor of the "Incandescent Light Bulb".

In 1840, British scientist Warren de la Rue enclosed a coiled platinum filament in a vacuum tube and passed an electric current through it. The design was based on the concept that the high melting point of platinum would allow it to operate at high temperatures and that the evacuated chamber would contain fewer gas molecules to react with the platinum, improving its longevity. Although an efficient design, the cost of the platinum made it impractical for commercial use.

In 1841, Frederick de Moleyns of England was granted the first patent for an incandescent lamp, with a design using platinum wires contained within a vacuum bulb.

In 1845, American John W. Starr acquired a patent for his incandescent light bulb involving the use of carbon filaments. He died shortly after obtaining the patent, and his invention was never produced commercially. Little else is known about him.

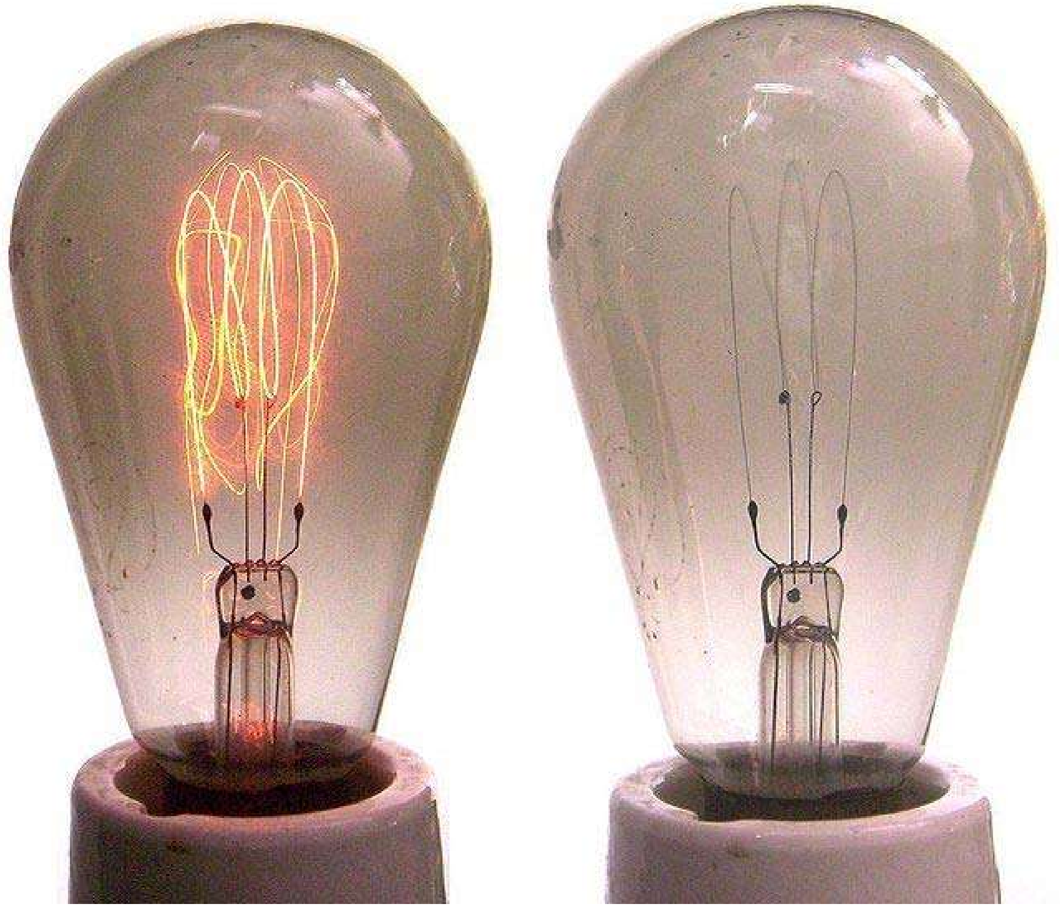
In 1851, Jean Eugène Robert-Houdin publicly demonstrated incandescent light bulbs on his estate in Blois, France. His light bulbs are on permanent display in the museum of the Château de Blois.

In 1872, Russian A. N. Lodygin invented an incandescent light bulb and obtained a Russian privilege. In 1874, he obtained an American patent for his invention. He used as burner two carbon rods of diminished section in a glass receiver, hermetically sealed, and filled with nitrogen, electrically arranged so that the current could be passed to the second carbon when the first had been consumed. Later he lived in the USA, changed his name to Alexander de Lodyguine and applied and obtained patents for incandescent lamps having molybdenum and tungsten filaments (US Patent No. 575,002 *Illuminant for Incandescent Lamps*, January 19, 1897) , that were then demonstrated at the Exposition Universelle of 1900 in Paris.

Heinrich Göbel, who used the name Henry Goebel in the USA, made a claim in 1893 during litigation over Edison's light bulb patent that, back in 1854, he had designed the first incandescent light bulb with a thin carbon-filament: a carbonized bamboo filament of high resistance, platinum lead-in wires in an all-glass envelope, and a high vacuum created by the process invented by Torricelli, and that in the following years he developed what many call the first practical incandescent light bulb. Judges of four courts raised doubts about the alleged Goebel anticipation. A research work published 2007 concluded that the story of the Goebel lamps in the 1850s is a legend.

In North America, parallel developments were taking place. On July 24, 1874, a Canadian patent was filed by a Toronto medical electrician named Henry Woodward and a colleague Mathew Evans. They built their lamps with different sizes and shapes of carbon rods held between electrodes in glass cylinders filled with nitrogen. Woodward and Evans attempted to commercialize their lamp, but were unsuccessful. They ended up selling their patent (U.S. Patent 0,181,613) to Thomas Edison in 1879.

Commercialization



Carbon filament lamp (E27 socket, 220 volts, approx. 30 watts, left side: running with 100 volts)

Joseph Swan (1828–1914) was a British physicist and chemist. In 1850, he began working with carbonized paper filaments in an evacuated glass bulb. By 1860, he was able to demonstrate a working device but the lack of a good vacuum and an adequate supply of electricity resulted in a short lifetime for the bulb and an inefficient source of light. By the mid-1870s better pumps became available, and Swan returned to his experiments.

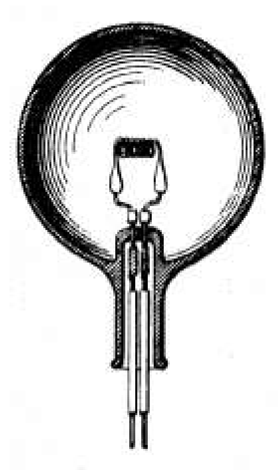
With the help of Charles Stearn, an expert on vacuum pumps, in 1878, Swan developed a method of processing that avoided the early bulb blackening. This received British Patent No 8 in 1880. On 18 December 1878, a lamp using a slender carbon rod was shown at a meeting of the Newcastle Chemical Society, and Swan gave a working demonstration at their meeting on 17 January 1879. It was also shown to 700 who attended a meeting of the Literary and Philosophical Society of Newcastle upon Tyne on 3 February 1879.

These lamps used a carbon rod from an arc lamp rather than a slender filament. Thus they had low resistance and required very large conductors to supply the necessary current, so they were not commercially practical, although they did furnish a demonstration of the possibilities of incandescent lighting with relatively high vacuum, a carbon conductor, and platinum lead-in wires. Besides requiring too much current for a central station electric system to be practical, they had a very short lifetime. Swan turned his attention to producing a better carbon filament and the means of attaching its ends. He devised a method of treating cotton to produce 'parchmentised thread' and obtained British Patent 4933 in 1880. From this year he began installing light bulbs in homes and landmarks in England. His house was the first in the world to be lit by a lightbulb and so the first house in the world to be lit by Hydro Electric power. In the early 1880s he had started his company. In 1881, the Savoy Theatre in the City of Westminister, London was lit by Swan incandescent lightbulbs, which was the first theatre, and the first public building in the world, to be lit entirely by electricity.

Thomas Edison began serious research into developing a practical incandescent lamp in 1878. Edison filed his first patent application for "Improvement In Electric Lights" on October 14, 1878. After many experiments with platinum and other metal filaments, Edison returned to a carbon filament. The first successful test was on October 22, 1879, and lasted 13.5 hours. Edison continued to improve this design and by November 4, 1879, filed for a U.S. patent for an electric lamp using "a carbon filament or strip coiled and connected ... to platina contact wires." Although the patent described several ways of creating the carbon filament including using "cotton and linen thread, wood splints, papers coiled in various ways," it was not until several months after the patent was granted that Edison and his team discovered that a carbonized bamboo filament could last over 1200 hours.

Hiram S. Maxim started a lightbulb company in 1878 to exploit his patents and those of William Sawyer. His United States Electric Lighting Company was the second company, after Edison, to sell practical incandescent electric lamps. They made their first commercial installation of incandescent lamps at the Mercantile Safe Deposit Company in New York City in the fall of 1880, about six months after the Edison incandescent lamps had been installed on the steamer Columbia. In October 1880, Maxim patented a method of coating carbon filaments with hydrocarbons to extend their life. Lewis Latimer, his employee at the time, developed an improved method of heat-treating them which reduced breakage and allowed them to be molded into novel shapes, such as the characteristic "M" shape of Maxim filaments. On January 17, 1882, Latimer received a patent for the "Process of Manufacturing Carbons," an improved method for the production of light bulb filaments, which was purchased by the United States Electric Light Company. Latimer patented other improvements such as a better way of attaching filaments to their wire supports.

In Britain, the Edison and Swan companies merged into the Edison and Swan United Electric Company (later known as Ediswan, that was ultimately incorporated into Thorn Lighting Ltd). Edison was initially against this combination, but after Swan sued him and won, Edison was eventually forced to cooperate, and the merger was made. Eventually, Edison acquired all of Swan's interest in the company. Swan sold his United States patent rights to the Brush Electric Company in June 1882.



U.S. Patent 0,223,898 by Thomas Edison for an improved electric lamp, January 27, 1880

In 1882, the first recorded set of miniature incandescent lamps for lighting a Christmas tree was installed. These did not become common in homes for many years.

The United States Patent Office gave a ruling October 8, 1883, that Edison's patents were based on the prior art of William Sawyer and were invalid. Litigation continued for a number of years. Eventually on October 6, 1889, a judge ruled that Edison's electric light improvement claim for "a filament of carbon of high resistance" was valid.

In the 1890s, the Austrian inventor Carl Auer von Welsbach worked on metal-filament mantles, first with platinum wire, and then osmium, and produced an operating version in 1898. In 1898, he patented the osmium lamp and started marketing it in 1902, the first commercial metal filament incandescent lamp.

In 1897, German physicist and chemist Walther Nernst developed the Nernst lamp, a form of incandescent lamp that used a ceramic globar and did not require enclosure in a vacuum or inert gas. Twice as efficient as carbon filament lamps, Nernst lamps were briefly popular until overtaken by lamps using metal filaments.

In 1903, Willis Whitnew invented a metal-coated carbon filament that would not blacken the inside of a light bulb.

On December 13, 1904, Hungarian Sándor Just and Croatian Franjo Hanaman were granted a Hungarian patent (No. 34541) for a tungsten filament lamp, that lasted longer and gave a brighter light than the carbon filament. Tungsten filament lamps were first marketed by the Hungarian company Tungsram in 1905, so this type is often called Tungsram-bulbs in many European countries.

In 1906, the General Electric Company patented a method of making filaments from sintered tungsten and in 1911, used ductile tungsten wire for incandescent light bulbs. The tungsten filament outlasted all other types.

In 1913, Irving Langmuir found that filling a lamp with inert gas instead of a vacuum resulted in twice the luminous efficacy and reduction of bulb blackening. In 1924, Marvin Pipkin, an American chemist, patented a process for frosting the inside of lamp bulbs without weakening them, and in 1947, he patented a process for coating the inside of lamps with silica.

In 1930, Hungarian Imre Bródy filled lamps with krypton gas in lieu of argon. He used krypton and/or xenon filling of bulbs. Since the new gas was expensive, he developed a process with his colleagues to obtain krypton from air. Production of krypton filled lamps based on his invention started at Ajka in 1937, in a factory co-designed by Polányi and Hungarian-born physicist Egon Orowan.

By 1964, improvements in efficiency and production of incandescent lamps had reduced the cost of providing a given quantity of light by a factor of thirty, compared with the cost at introduction of Edison's lighting system

Consumption of incandescent light bulbs grew rapidly in the United States. In 1885, an estimated 300,000 general lighting service lamps were sold, all with carbon filaments. When tungsten filament were introduced, there were about 50 million lamp sockets in the United States. In 1914, 88.5 million lamps were used, (only 15% with carbon filaments), and by 1945, annual sales of lamps were 795 million (more than 5 lamps per person per year).

Cartels

Between 1924 and 1939, the international market for incandescent light bulbs was controlled by the Phoebus cartel, which dictated wholesale prices and whose members controlled most of the world market for lamps.

Efficiency and environmental impact

Xenon Halogen Lamp (105 W) with an E27 base, intended for direct replacement of a non-halogen bulb

Approximately 90% of the power consumed by an incandescent light bulb is emitted as heat, rather than as visible light.

The effectiveness of an electric lighting source is determined by two factors, the relative visibility of electromagnetic radiation, and the rate at which the source converts electric power into electromagnetic radiation.

Luminous efficacy of a light source is a ratio of the visible light energy emitted (the *luminous flux*) to the total power input to the lamp. Visible light is measured in lumens, a unit which is defined in part by the differing sensitivity of the human eye to different wavelengths of light. Not all wavelengths of visible electromagnetic energy are equally effective at stimulating the human eye; the luminous efficacy of radiant energy is a measure of how well the distribution of energy matches the perception of the eye. The maximum efficacy possible is 683 lm/W for monochromatic green light at 555 nanometres wavelength, the peak sensitivity of the human eye. For white light, the maximum luminous efficacy is around 240 lumens per watt, but the exact value is not unique because the human eye can perceive many different mixtures of visible light as "white".

The chart below lists values of overall luminous efficacy and efficiency for several types of general service, 120-volt, 1000-hour lifespan incandescent bulb, and several idealized light sources.

Type	Overall luminous efficiency	Overall luminous efficacy (lm/W)
40 W tungsten incandescent	1.9%	12.6
60 W tungsten incandescent	2.1%	14.5
100 W tungsten incandescent	2.6%	17.5
glass halogen	2.3%	16
quartz halogen	3.5%	24
high-temperature incandescent	5.1%	35
ideal black-body radiator at 4000 K (or a class K star like Arcturus)	7.0%	47.5
ideal black-body radiator at 7000 K (or a class F star like Procyon)	14%	95
ideal monochromatic 555 nm (green) source	100%	683

Unfortunately, the spectrum emitted by a blackbody radiator does not match the sensitivity characteristics of the human eye. Tungsten filaments radiate mostly infrared radiation at temperatures where they remain solid (below 3683 kelvins / 3410 °C / 6,170 °F). Donald L. Klipstein explains it this way: "An ideal thermal radiator produces visible light most efficiently at temperatures around 6300 °C (6600 K or 11,500 °F). Even at this high temperature, a lot of the radiation is either infrared or ultraviolet, and the theoretical luminous efficiency is 95 lumens per watt." No known material can be used as a filament at this ideal temperature, which is hotter than the sun's surface. An upper limit for incandescent lamp luminous efficacy is around 52 lumens per watt, the theoretical value emitted by tungsten at its melting point.

For a given quantity of light, an incandescent light bulb produces more heat (and consumes more power) than a fluorescent lamp. Incandescent lamps' heat output increases load on air conditioning in the summer, but the heat from lighting can contribute to building heating in cold weather.

High-quality halogen incandescent lamps have higher efficacy, which will allow a 60-watt bulb to provide nearly as much light as a non-halogen 100-watt bulb. Also, a lower-wattage halogen lamp can be designed to produce the same amount of light as a 600-watt non-halogen lamp, but with much longer life.

Many light sources, such as the fluorescent lamp, high-intensity discharge lamps and LED lamps offer higher efficiency, and some have been designed to be retrofitted in existing fixtures. These devices produce light by luminescence, instead of heating a filament to incandescence. These mechanisms produce discrete spectral lines and so don't have the broad "tail" of wasted invisible infrared emissions produced by incandescent emitters. By careful selection of which electron energy level transitions are used, the spectrum emitted can be tuned to either mimic the appearance of incandescent sources or else produce different color temperatures of white for visible light.

Cost of lighting

The initial cost of an incandescent bulb is small compared to the cost of the energy it uses over its lifetime. A comparison of incandescent lamp operating cost with other light sources must consider the luminous efficacy produced by each lamp. The comparison must include illumination requirements, capital cost of the lamp, labor cost to replace lamps, various depreciation factors for light output as the lamp ages, effect of lamp operation on heating and air conditioning systems, and energy consumption as well.

Measures to ban its use

Due to the higher energy usage of incandescent light bulbs in comparison to more energy efficient alternatives, such as compact fluorescent lamps and LED lamps, many governments have introduced measures to ban their use, by setting minimum efficacy standards higher than can be achieved by general service lamps. However, there has been much resistance to these policies owing to the low cost of incandescent bulbs, the instant availability of light, and possible ill health effects including the problems of mercury contamination with CFLs. Varying and unpredictable quality of current CFLs and LED lamps adds to the resistance.

Efforts to improve efficiency

Due to the measures noted above, there have been recent efforts to improve the efficiency of incandescents. In 2007, the consumer lighting division of General Electric announced a "high efficiency incandescent" (HEI) lamp project, which they claimed would ultimately be as much as four times more efficient than current incandescents, although their initial production goal was to be approximately two times more efficient. The HEI program was quietly terminated in 2008 due to slow progress.

U.S. Department of Energy research at Sandia National Laboratories initially indicated the potential for dramatically improved efficiency from a photonic lattice filament. However, later work indicated that initially promising results were in error.

Prompted by U.S. legislation mandating increased bulb efficiency by 2012, new "hybrid" incandescent bulbs have been introduced by Philips. The "Halogena Energy Saver" incandescent is 30 percent more efficient than traditional designs, using a special chamber to reflect formerly wasted heat back to the filament to provide additional lighting power.

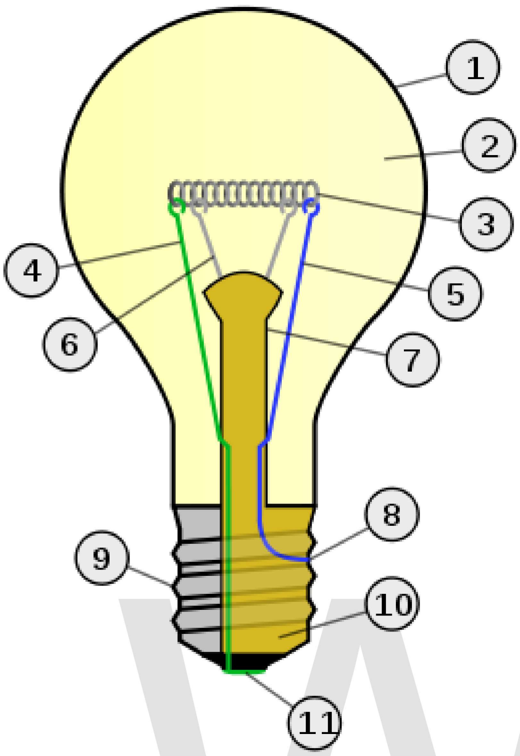
Construction

Incandescent light bulbs consist of a glass enclosure (the envelope, or bulb) with a filament of tungsten wire inside the bulb, through which an electric current is passed. Contact wires and a base with two (or more) conductors provide electrical connections to the filament. Incandescent light bulbs usually contain a stem or glass mount anchored to the bulb's base that allows the electrical contacts to run through the envelope without gas/air leaks. Small wires embedded in the stem in turn support the filament and/or its lead wires. The bulb is filled with an inert gas such as argon to reduce evaporation and prevent oxidation of the filament.

An electric current heats the filament to typically 2,000 to 3,300 K (3,140 to 5,480 °F)), well below tungsten's melting point of 3,695 K (6,191 °F). Filament temperatures depend on the filament type, shape, size, and amount of current drawn. The heated filament emits light that approximates a continuous spectrum. The useful part of the emitted energy is visible light, but most energy is given off as heat in the near-infrared wavelengths.

Three-way light bulbs have two filaments and three conducting contacts in their bases. The filaments share a common ground, and can be lit separately or together. Common wattages include 30–70–100, 50–100–150, and 100–200–300, with the first two numbers referring to the individual filaments, and the third giving the combined wattage.

While most light bulbs have clear or frosted glass, other kinds are also produced, including the various colors used for Christmas tree lights and other decorative lighting. Neodymium-containing glass is sometimes used to provide a more natural-appearing light.



1. Outline of Glass bulb
2. Low pressure inert gas (argon, neon, nitrogen)
3. Tungsten filament
4. Contact wire (goes out of stem)
5. Contact wire (goes into stem)
6. Support wires
7. Stem (glass mount)
8. Contact wire (goes out of stem)
9. Cap (sleeve)
10. Insulation (vitrite)
11. Electrical contact

Many arrangements of electrical contacts are used. Large lamps may have a screw base (one or more contacts at the tip, one at the shell) or a bayonet base (one or more contacts on the base, shell used as a contact or used only as a mechanical support). Some tubular lamps have an electrical contact at either end. Miniature lamps may have a wedge base and wire contacts, and some automotive and special purpose lamps have screw terminals for connection to wires. Contacts in the lamp socket allow the electric current to pass through the base to the filament. Power ratings for incandescent light bulbs range from about 0.1 watt to about 10,000 watts.

The glass bulb of a general service lamp can reach temperatures between 200 and 260 °C (392 and 500 °F). Lamps intended for high power operation or used for heating purposes will have envelopes made of hard glass or fused quartz.

Manufacturing

Early lamps were laboriously hand-assembled; however, after automatic machinery was developed cost of lamps fell.

In manufacturing the glass bulb, a type of "ribbon machine" is used. A continuous ribbon of glass is passed along a conveyor belt, heated in a furnace, and then blown by precisely aligned air nozzles through holes in the conveyor belt into molds. Thus the glass bulbs are created. After the bulbs are blown, and cooled, they are cut off of the ribbon machine. A typical machine of this sort produces 50,000 bulbs per hour.

Filament

The first successful light bulb filaments were made of carbon (from carbonized paper or bamboo). Early carbon filaments had a negative temperature coefficient of resistance -- as they got hotter, their electrical resistance decreased. This made the lamp sensitive to fluctuations in the power supply, since a small increase of voltage would cause the filament to heat up, reducing its resistance and causing it to draw even more power and heat even further. In the "flashing" process, carbon filaments were heated by current passing through them, while in an evacuated vessel containing hydrocarbon (gasoline) vapor. The carbon deposited by this treatment improved the uniformity and strength of filaments, and their efficiency. A metallized or graphitized filament was first heated in a high-temperature oven before flashing and lamp assembly; this transformed the carbon into graphite, which further strengthened and smoothed the filament, and as a byproduct had the advantage of changing the lamp to a positive temperature coefficient like a metallic conductor. This helped stabilize power consumption, temperature and light output against minor variations in supply voltage.

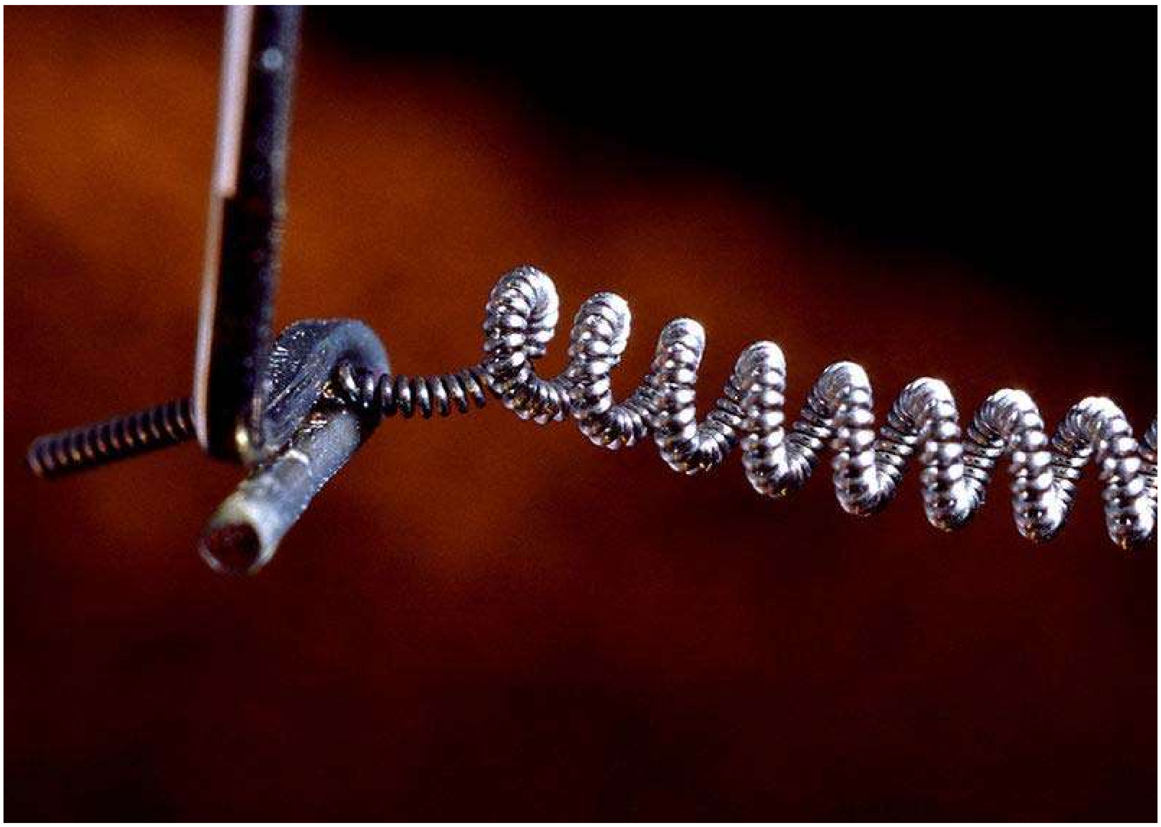
In 1902, the Siemens company developed a tantalum lamp filament. These lamps were more efficient than even graphitized carbon filaments and could operate at higher temperatures. Since the metal had a lower resistivity than carbon, the tantalum lamp filament was quite long and required multiple internal supports. The metal filament had the property of gradually shortening in use; the filaments were installed with large loops that tightened in use. This made lamps in use for several hundred hours quite fragile. Metal filaments had the property of breaking and re-welding, though this would usually decrease resistance and shorten the life of the filament. General Electric bought the rights to use tantalum filaments and produced them in the United States until 1913.

From 1898 to around 1905, osmium was also used as a lamp filament in Europe, but the metal was so expensive that used broken lamps could be returned for part credit. It could not be made for 110 V or 220 V so several lamps were wired in series for use on standard voltage circuits.

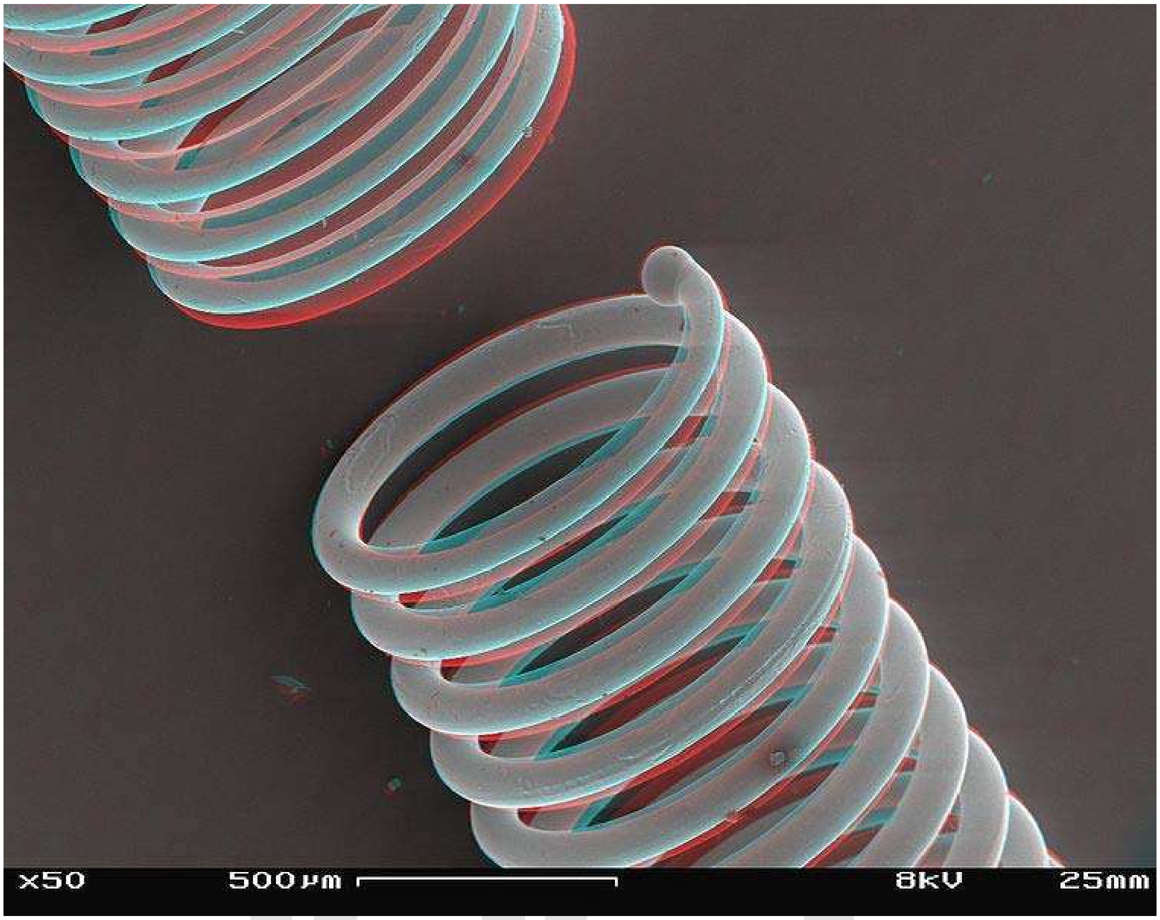
In 1906, the tungsten filament was introduced. Tungsten metal was initially not available in a form that allowed it to be drawn into fine wires. Filaments made from sintered tungsten powder were quite fragile. By 1910, a process was developed by William D. Coolidge at General Electric for production of a ductile form of tungsten. The process required pressing chemically produced tungsten powder into bars, then several steps of sintering, swaging, and then wire drawing. It was found that very pure tungsten formed filaments that sagged in use, and that a very small "doping" treatment with potassium, silicon, and aluminum oxides at the level of a few hundred parts per million greatly improved the life and durability of the tungsten filaments.

To improve the efficiency of the lamp, the filament usually consists of coils of coiled fine wire, also known as a 'coiled coil.' For a 60-watt 120-volt lamp, the uncoiled length of the tungsten filament is usually 22.8 inches (580 mm), and the filament diameter is 0.0018 inches (0.046 mm). The advantage of the coiled coil is that evaporation of the tungsten filament is at the rate of a tungsten cylinder having a diameter equal to that of the coiled coil. The coiled-coil filament evaporates more slowly than a straight filament of the same surface area and light-emitting power. If the filament is then run hotter to bring back evaporation to the same rate, the resulting filament is a more efficient light source.

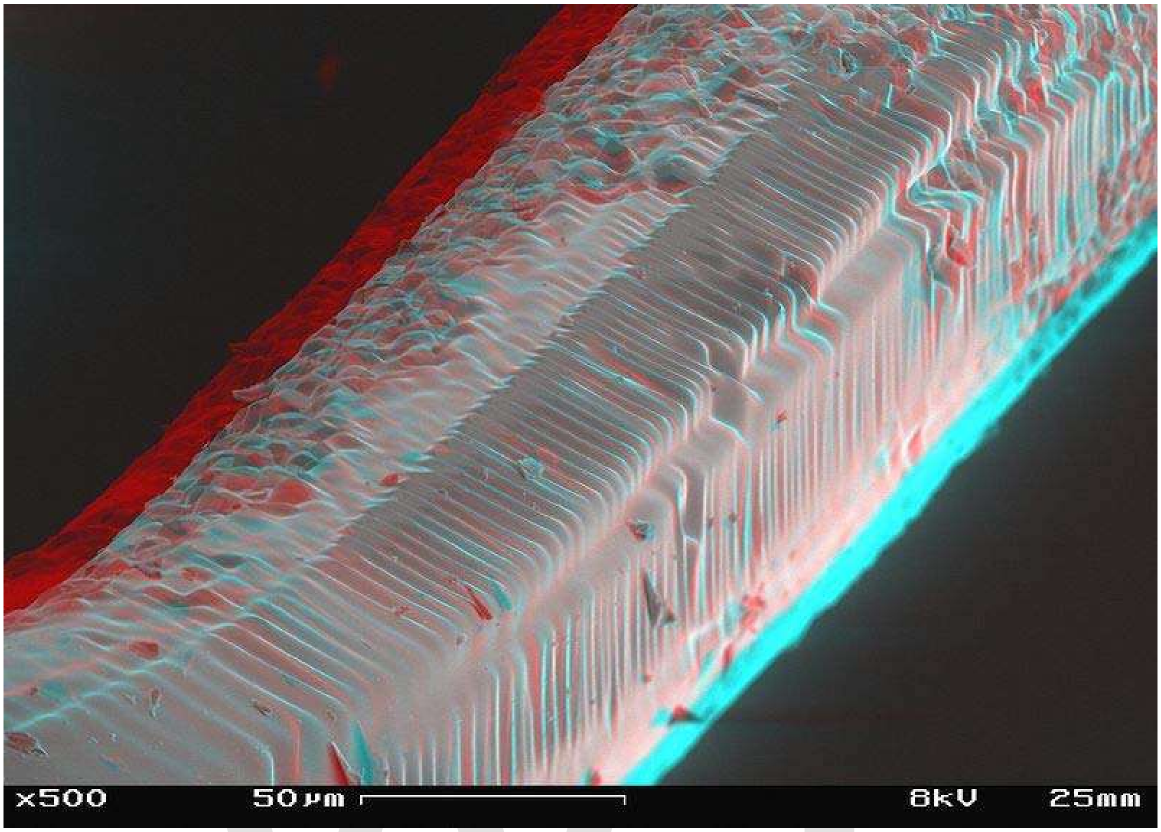
There are several different shapes of filament used in lamps, with differing characteristics. Manufacturers designate the types with codes such as C-6, CC-6, C-2V, CC-2V, C-8, CC-88, C-2F, CC-2F, C-Bar, C-Bar-6, C-8I, C-2R, CC-2R, and Axial.



Filament of a 200-watt incandescent lightbulb highly magnified



Filament of a burnt-out 50-watt incandescent lightbulb in an SEM in stereoscopic mode, presented as an anaglyph image.



Filament of a 50-watt incandescent lightbulb in an SEM in stereoscopic mode, presented as an anaglyph image.

Electrical filaments are also used in hot cathodes of fluorescent lamps and vacuum tubes as a source of electrons or in vacuum tubes to heat an electron-emitting electrode.

Reducing filament evaporation

One of the problems of the standard electric light bulb is evaporation of the filament. Small variations in resistivity along the filament cause "hot spots" to form at points of higher resistivity; a variation of diameter of only 1% will cause a 25% reduction in service life. The hot spots evaporate faster than the rest of the filament, increasing resistance at that point—a positive feedback that ends in the familiar tiny gap in an otherwise healthy-looking filament. Irving Langmuir found that an inert gas, instead of vacuum, would retard evaporation. General service incandescent light bulbs over about 25 watts in rating are now filled with a mixture of mostly argon and some nitrogen, or sometimes krypton. Xenon gas, much more expensive, is used occasionally in small bulbs, such as those for flashlights. Since a filament breaking in a gas-filled bulb can form an electric arc, which may spread between the terminals and draw very heavy current, intentionally thin lead-in wires or more elaborate protection devices are therefore often used as fuses built into the light bulb. More nitrogen is used in higher-voltage lamps to reduce the possibility of arcing.

During ordinary operation, the tungsten of the filament evaporates; hotter, more-efficient filaments evaporate faster. Because of this, the lifetime of a filament lamp is a trade-off between efficiency and longevity. The trade-off is typically set to provide a lifetime of several hundred to 2,000 hours for lamps used for general illumination. Theatrical, photographic, and projection lamps may have a useful life of only a few hours, trading life expectancy for high output in a compact form. Long-life general service lamps have lower efficiency but are used where the cost of changing the lamp is high compared to the value of energy used.

Filament notching describes another phenomenon that limits the life of lamps. Lamps operated on direct current develop random stair-step irregularities on the filament surface, reducing the cross section and further increasing heat and evaporation of tungsten at these points. In small lamps operated on direct current, lifespan may be cut in half compared to AC operation. Different alloys of tungsten and rhenium can be used to counteract the effect.

If a light bulb envelope leaks, the hot tungsten filament reacts with air, yielding an aerosol of brown tungsten nitride, brown tungsten dioxide, violet-blue tungsten pentoxide, and yellow tungsten trioxide that then deposits on the nearby surfaces or the bulb interior.

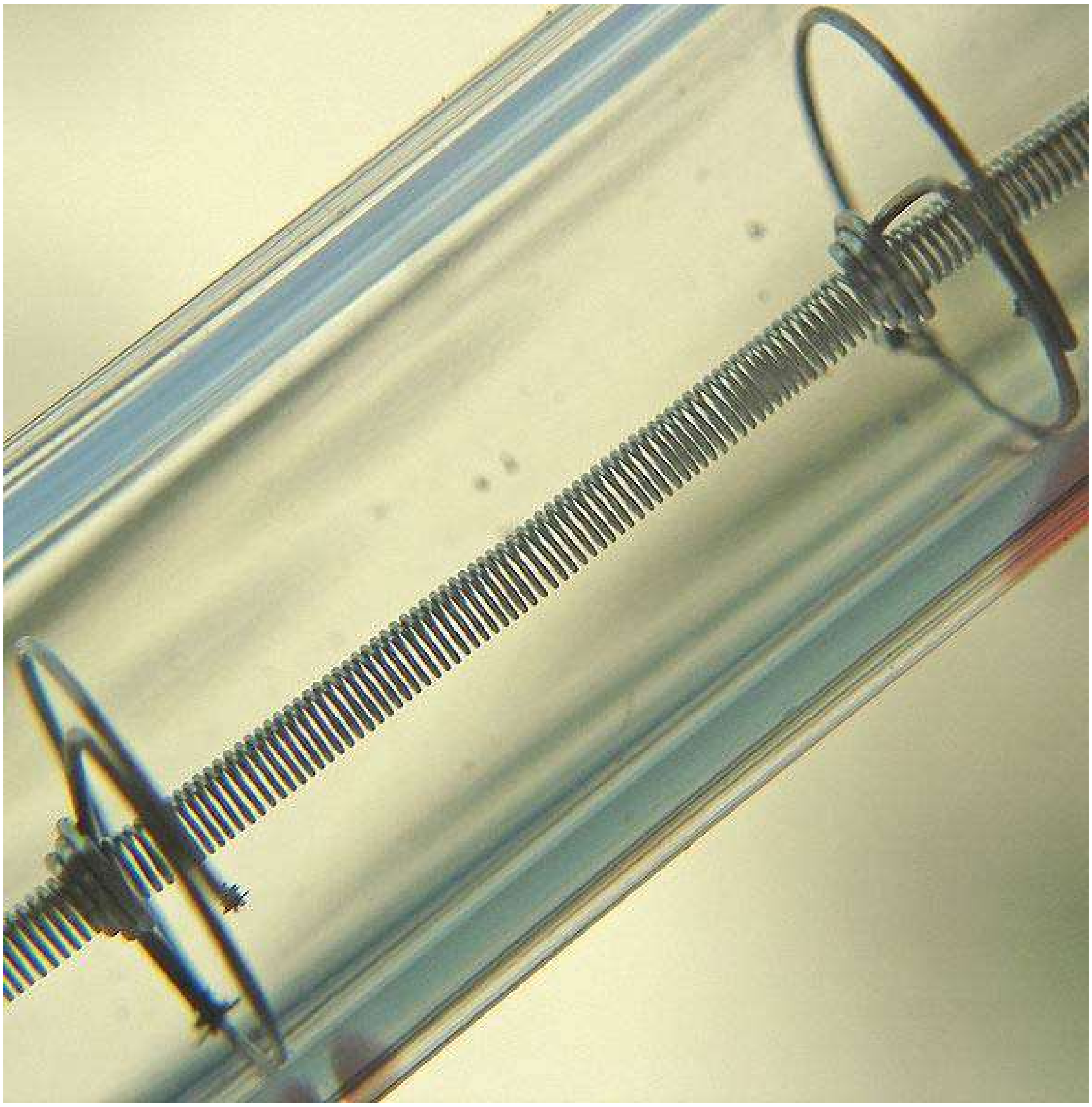
Bulb blackening

In a conventional lamp, the evaporated tungsten eventually condenses on the inner surface of the glass envelope, darkening it. For bulbs that contain a vacuum, the darkening is uniform across the entire surface of the envelope. When a filling of inert gas is used, the evaporated tungsten is carried in the thermal convection currents of the gas, depositing preferentially on the uppermost part of the envelope and blackening just that portion of the envelope. An incandescent lamp that gives 93% or less of its initial light output at 75% of its rated life is regarded as unsatisfactory, when tested according to IEC Publication 60064. Light loss is due to filament evaporation and bulb blackening. Study of the problem of bulb blackening led to the discovery of the Edison effect, thermionic emission and invention of the vacuum tube.

A very small amount of water vapor inside a light bulb can significantly affect lamp darkening. Water vapor dissociates into hydrogen and oxygen at the hot filament. The oxygen attacks the tungsten metal, and the resulting tungsten oxide particles travel to cooler parts of the lamp. Hydrogen from water vapor reduces the oxide, reforming water vapor and continuing this *water cycle*. The equivalent of a drop of water distributed over 500,000 lamps will significantly increase darkening. Small amounts of substances such as zirconium are placed within the lamp as a getter to react with any oxygen that may bake out of the lamp components during operation.

Some old, high-powered lamps used in theater, projection, searchlight, and lighthouse service with heavy, sturdy filaments contained loose tungsten powder within the envelope. From time to time, the operator would remove the bulb and shake it, allowing the tungsten powder to scrub off most of the tungsten that had condensed on the interior of the envelope, removing the blackening and brightening the lamp again.

Halogen lamps



Close-up of a tungsten filament inside a halogen lamp. The two ring-shaped structures left and right are filament supports.

The halogen lamp reduces uneven evaporation of the filament and darkening of the envelope by filling the lamp with a halogen gas at low pressure, rather than an inert gas. The halogen cycle increases the lifetime of the bulb and prevents its darkening by redepositing tungsten from the inside of the bulb back onto the filament. The halogen lamp can operate its filament at a higher temperature than a standard gas filled lamp of similar power without loss of operating life.

Incandescent arc lamps

A variation of the incandescent lamp did not use a hot wire filament, but instead used an arc struck on a spherical bead electrode to produce heat. The electrode then became incandescent, with the arc contributing little to the light produced. Such lamps were used for projection or illumination for scientific instruments such as microscopes. These arc lamps ran on relatively low voltages and incorporated tungsten filaments to start ionization within the envelope. They provided the intense concentrated light of an arc lamp but were easier to operate. Developed around 1915, these lamps were displaced by mercury and xenon arc lamps.

Electrical characteristics

Incandescent lamps are nearly pure resistive loads with a power factor of 1. This means the actual power consumed (in watts) and the apparent power (in volt-amperes) are equal. The actual resistance of the filament is temperature-dependent. The cold resistance of tungsten-filament lamps is about 1/15 the hot-filament resistance when the lamp is operating. For example, a 100-watt, 120-volt lamp has a resistance of 144 ohms when lit, but the cold resistance is much lower (about 9.5 ohms). Since incandescent lamps are resistive loads, simple triac dimmers can be used to control brightness. Electrical contacts may carry a "T" rating symbol indicating that they are designed to control circuits with the high inrush current characteristic of tungsten lamps. For a 100-watt, 120-volt general-service lamp, the current stabilizes in about 0.10 seconds, and the lamp reaches 90% of its full brightness after about 0.13 seconds.

Power

Incandescent light bulbs are usually marketed according to the electrical power consumed. This is measured in watts and depends mainly on the resistance of the filament, which in turn depends mainly on the filament's length, thickness, and material. For two bulbs of the same voltage, type, color, and clarity, the higher-powered bulb gives more light.

The table shows the approximate typical output, in lumens, of standard incandescent light bulbs at various powers. Note that the lumen values for "soft white" bulbs will generally be slightly lower than for standard bulbs at the same power, while clear bulbs will usually emit a slightly brighter light than correspondingly powered standard bulbs.

Physical characteristics

Bulb shapes, sizes, and terms

Incandescent light bulbs come in a range of shapes and sizes. The names of the shapes may be slightly different in some regions. Many of these shapes have a designation consisting of one or more letters followed by one or more numbers, e.g. A55 or PAR38.

The letters represent the shape of the bulb. The numbers represent the maximum diameter, either in ⅛ of an inch, or in millimetres, depending on the shape and the region. For example, 63 mm reflectors are designated R63, but in the U.S. they are known as R20 (2.5 in). However, in both regions, a PAR38 reflector is known as PAR38. In Australia an R80 is 1 in in diameter.

Common shapes:

General Service
: Light emitted in (nearly) all directions. Available either clear or frosted.
: Types: General (A), Mushroom

High Wattage General Service
: Lamps greater than 200 watts.
: Types: Pear-shaped (PS)

Decorative
: lamps used in chandeliers, etc.
: Types: candle (B), twisted candle, bent-tip candle (CA & BA), flame (F), fancy round (P), globe (G)

Reflector (R)
: Reflective coating inside the bulb directs light forward. Flood types (FL) spread light. Spot types (SP) concentrate the light. Reflector (R) bulbs put approximately double the amount of light (foot-candles) on the front central area as General Service (A) of same wattage.
: Types: Standard reflector (R), elliptical reflector (ER), crown-silvered

Parabolic aluminized reflector (PAR)
: Parabolic aluminized reflector (PAR) bulbs control light more precisely. They produce about four times the concentrated light intensity of general service (A), and are used in recessed and track lighting. Weatherproof casings are available for outdoor spot and flood fixtures.
: 120 V sizes: PAR 16, 20, 30, 38, 56 and 64
: 230 V sizes: Par 38, 56 and 64
: Available in numerous spot and flood beam spreads. Like all light bulbs, the number represents the diameter of the bulb in ⅛ of an inch. Therefore, a PAR 16 is 2 in in diameter, a PAR 20 is 2.5 in in diameter, PAR 30 is 3.75 in and a PAR 38 is 4.75 in in diameter.

Multifaceted reflector (MR)

HIR
: "HIR" is a GE designation for a lamp with an infrared reflective coating. Since less heat escapes, the filament burns hotter and more efficiently. The Osram designation for a similar coating is "IRC".

Lamp bases

40-watt light bulbs with standard E10, E14 and E27 Edison screw base

Very small lamps may have the filament support wires extended through the base of the lamp, and can be directly soldered to a printed circuit board for connections. Some reflector-type lamps include screw terminals for connection of wires. Most lamps have metal bases that fit in a socket to support the lamp and conduct current to the filament wires. In the late 19th century, manufacturers introduced a multitude of incompatible lamp bases. General Electric introduced standard base sizes for tungsten incandescent lamps under the Mazda trademark in 1909. This standard was soon adopted across the United States, and the Mazda name was used by many manufacturers under license through 1945. Today most incandescent lamps for general lighting service use an Edison screw in candelabra, intermediate, or standard or mogul sizes, or double contact bayonet base. Bayonet base lamps are frequently used in automotive lamps to resist loosening due to vibration. A bipin base is often used for halogen or reflector lamps.

Lamp bases may be secured to the bulb with a cement, or by mechanical crimping to indentations molded into the glass bulb.

The double-contact bayonet cap on an incandescent bulb

Miniature lamps used for some automotive lamps or decorative lamps have wedge bases that have a partial plastic or even completely glass base. In this case, the wires wrap around to the outside of the bulb, where they press against the contacts in the socket. Miniature Christmas bulbs use a plastic wedge base as well.

Lamps intended for use in optical systems (such as film projectors, microscope illuminators, or stage lighting instruments have bases with alignment features so that the filament is positioned accurately within the optical system. A screw-base lamp may have a random orientation of the filament when the lamp is installed in the socket.

Voltage, light output, and lifetime

Incandescent lamps are very sensitive to changes in the supply voltage. These characteristics are of great practical and economic importance.

For a supply voltage V near the rated voltage of the lamp:

- *Light* output is approximately proportional to $V^{3.4}$
- *Power* consumption is approximately proportional to $V^{1.6}$
- *Lifetime* is approximately proportional to V^{-16}
- *Color temperature* is approximately proportional to $V^{0.42}$

This means that a 5% reduction in operating voltage will more than double the life of the bulb, at the expense of reducing its light output by about 20%. This may be a very acceptable trade off for a light bulb that is in a difficult-to-access location (for example, traffic lights or fixtures hung from high ceilings). Long-life bulbs take advantage of this trade-off. Since the value of the electric power they consume is much more than the value of the lamp, general service lamps emphasize efficiency over long operating life. The objective is to minimize the cost of light, not the cost of lamps.

The relationships above are valid for only a few percent change of voltage around rated conditions, but they do indicate that a lamp operated at much lower than rated voltage could last for hundreds of times longer than at rated conditions, albeit with greatly reduced light output. The *Centennial Light* is a light bulb that is accepted by the *Guinness Book of World Records* as having been burning almost continuously at a fire station in Livermore, California, since 1901. However, the bulb is powered by only four watts. A similar story can be told of a 40-watt bulb in Texas that has been illuminated since September 21, 1908. It once resided in an opera house where notable celebrities stopped to take in its glow, but is now in an area museum.

In flood lamps used for photographic lighting, the tradeoff is made in the other direction. Compared to general-service bulbs, for the same power, these bulbs produce far more light, and (more importantly) light at a higher color temperature, at the expense of greatly reduced life (which may be as short as two hours for a type P1 lamp). The upper limit to the temperature at which metal incandescent bulbs can operate is the melting point of the metal. Tungsten is the metal with the highest melting point, 3,695 K (6,191 °F). A 50-hour-life projection bulb, for instance, is designed to operate only 50 °C (122 °F) below that melting point. Such a lamp may achieve up to 22 lumens per watt, compared with 17.5 for a 750-hour general service lamp.

Lamps designed for different voltages have different luminous efficacy. For example, a 100-watt, 120-volt lamp will produce about 17.1 lumens per watt. A lamp with the same rated lifetime but designed for 230 V would produce only around 12.8 lumens per watt, and a similar lamp designed for 30 volts (train lighting) would produce as much as 19.8 lumens per watt. Lower voltage lamps have a thicker filament, for the same power rating. They can run hotter for the same lifetime before the filament evaporates.

The wires used to support the filament make it mechanically stronger, but remove heat, creating another tradeoff between efficiency and long life. Many general-service 120-volt lamps use no additional support wires, but lamps designed for "rough service" or "vibration service" may have as many as five. Low-voltage lamps have filaments made of heavier wire and do not require additional support wires.

Very low voltages are inefficient since the lead wires would conduct too much heat away from the filament, so the practical lower limit for incandescent lamps is 1.5 volts. Very long filaments for high voltages are fragile, and lamp bases become more difficult to insulate, so lamps for illumination are not made with rated voltages over 300 volts. Some infrared heating elements are made for higher voltages, but these use tubular bulbs with widely separated terminals.

Health issues

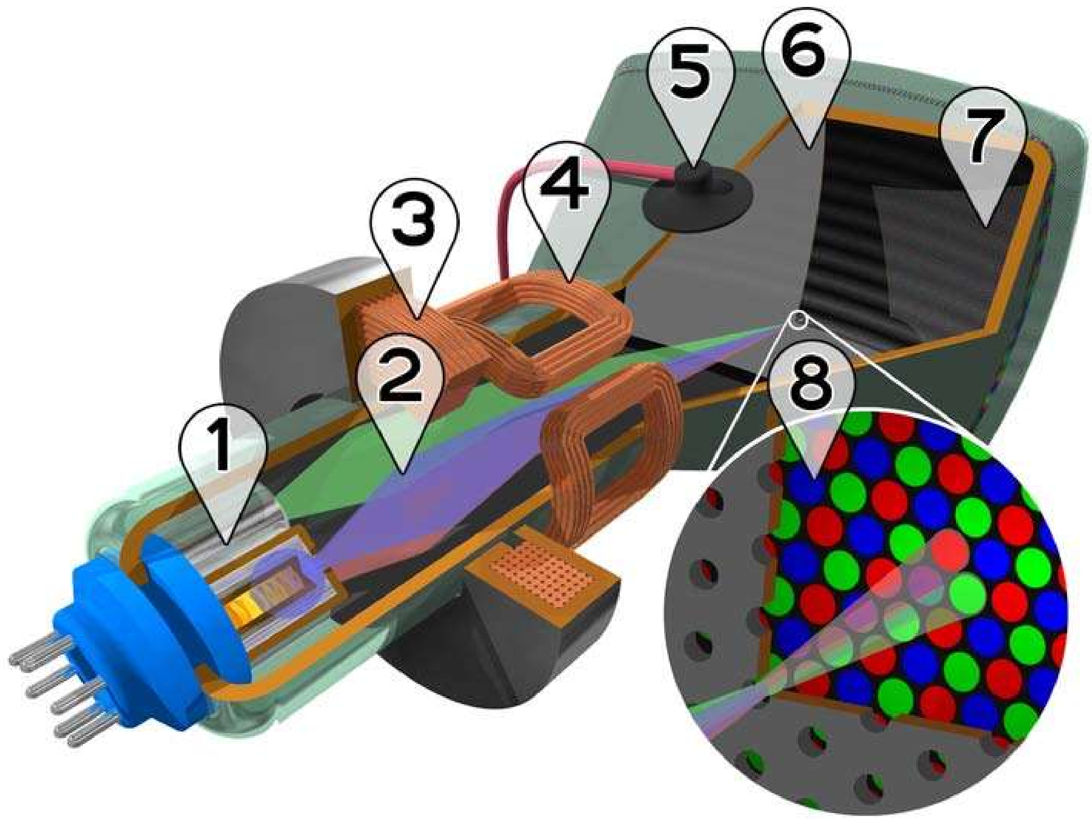
Although some sources claim fluorescent lighting causes more health problems than incandescent lighting, more research needs to be done in this field. According to the European Commission Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) in 2008, the only property of compact 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.

Radio interference

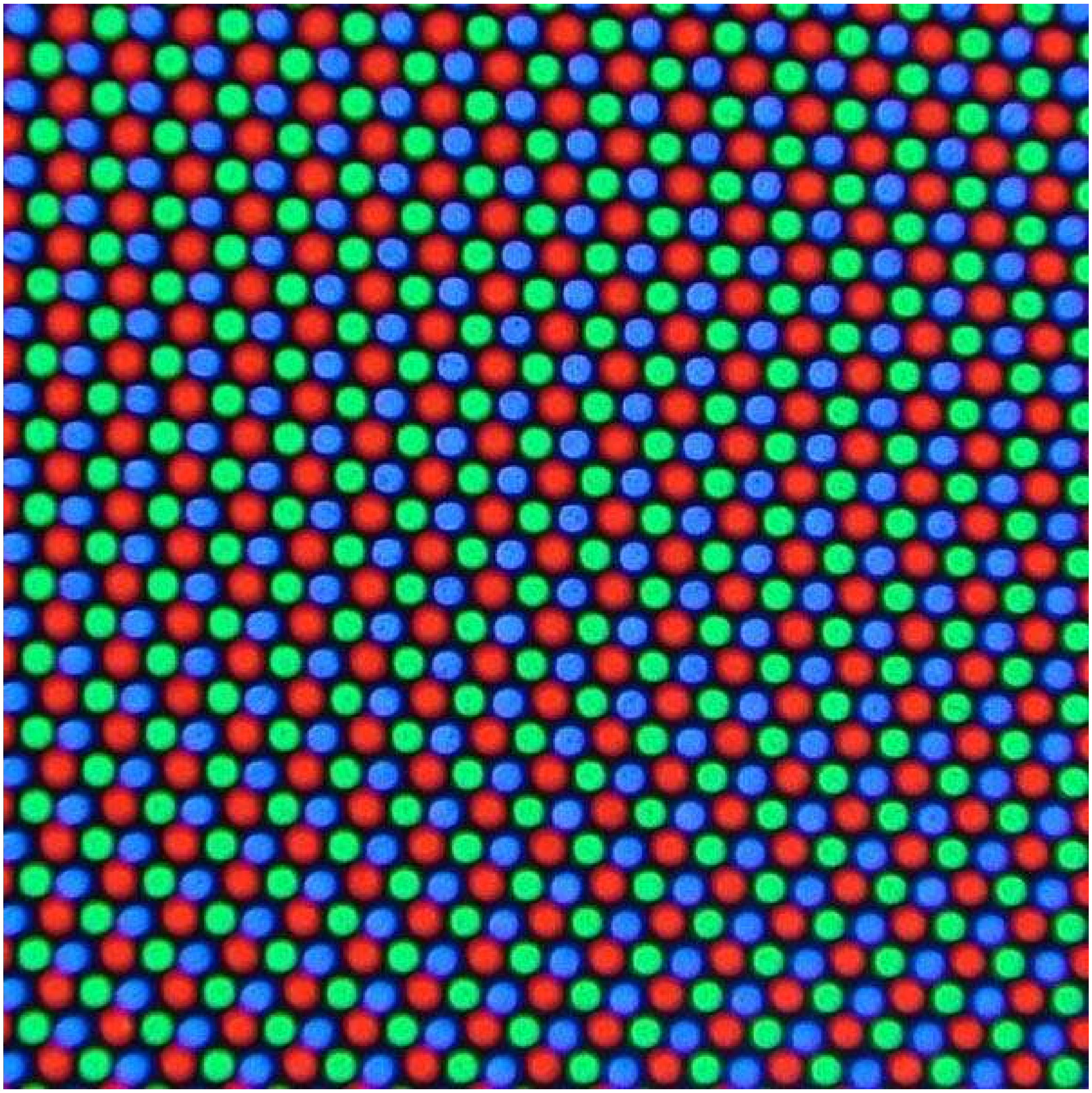
Incandescent bulbs do not produce significant radio frequency interference, a concern with many other light sources, such as most LED and fluorescent lamps.

Chapter- 2

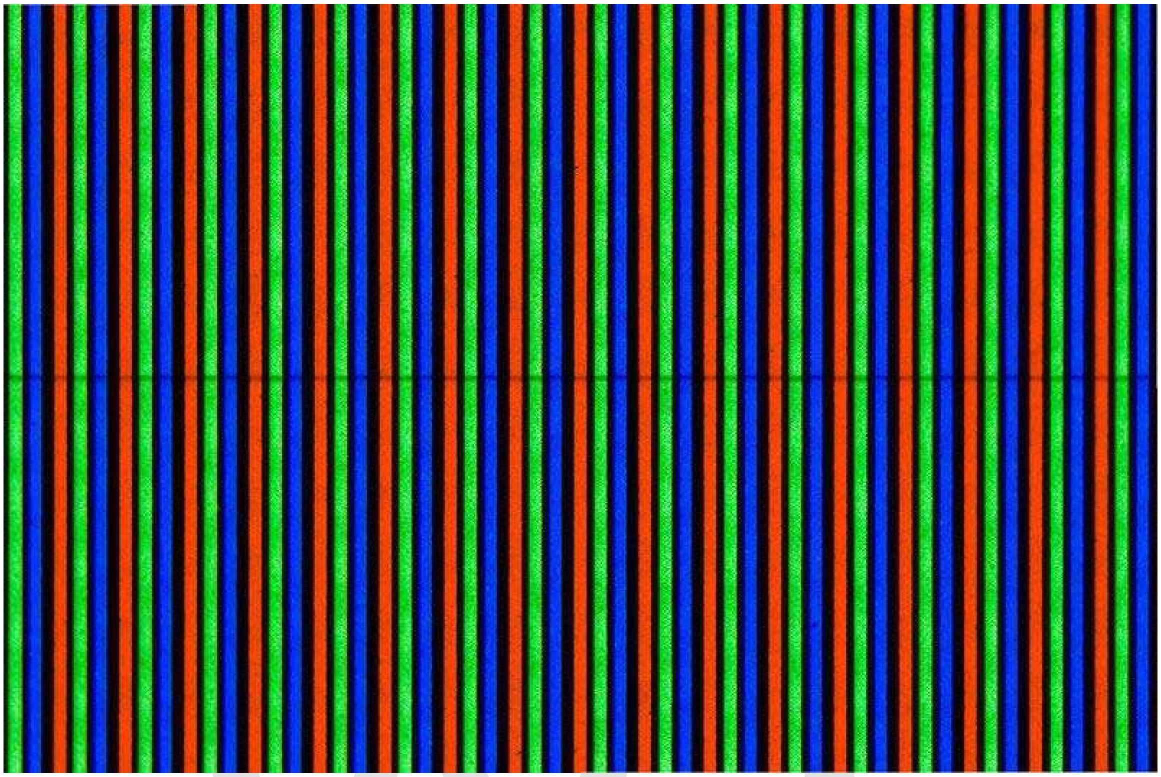
Cathode Ray Tube



Cutaway rendering of a color CRT:
1. Three Electron guns (for red, green, and blue phosphor dots)
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen



Magnified view of a shadow mask color CRT



Magnified view of an aperture grille color CRT

The **Cathode Ray Tube** (**CRT**) is a vacuum tube containing an electron gun (a source of electrons) and a fluorescent screen, with internal or external means to accelerate and deflect the electron beam, used to create images in the form of light emitted from the fluorescent screen. The image may represent electrical waveforms (oscilloscope), pictures (television, computer monitor), radar targets and others.

The CRT uses an evacuated glass envelope which is large, deep, heavy, and relatively fragile.

History

A common CRT used in computer monitors and television sets

The experimentation of cathode rays is largely accredited to J.J. Thomson, a British physicist who, in his three famous experiments, was able to deflect cathode rays, a fundamental function of the modern CRT. The earliest version of the CRT was invented by the German physicist Ferdinand Braun in 1897 and is also known as the *Braun tube*. It was a cold-cathode diode, a modification of the Crookes tube with a phosphor-coated screen.

In 1907, Russian scientist Boris Rosing used a CRT in the receiving end of an experimental video signal to form a picture. He managed to display simple geometric shapes onto the screen, which marked the first time that CRT technology was used for what is now known as television.

The first cathode ray tube to use a hot cathode was developed by John B. Johnson (who gave his name to the term Johnson noise) and Harry Weiner Weinhart of Western Electric, and became a commercial product in 1922.

Overview

A cathode ray tube is a vacuum tube which consists of one or more electron guns, possibly internal electrostatic deflection plates, and a phosphor target. In television sets and computer monitors, the entire front area of the tube is scanned repetitively and systematically in a fixed pattern called a raster. An image is produced by controlling the intensity of each of the three electron beams, one for each additive primary color (red, green, and blue) with a video signal as a reference. In all modern CRT monitors and televisions, the beams are bent by *magnetic deflection*, a varying magnetic field generated by coils and driven by electronic circuits around the neck of the tube, although electrostatic deflection is commonly used in oscilloscopes, a type of diagnostic instrument.

Electron gun

Oscilloscope CRTs

In oscilloscope CRTs, electrostatic deflection is used, rather than the magnetic deflection commonly used with television and other large CRTs. The beam is deflected horizontally by applying an electric field between a pair of plates to its left and right, and vertically by applying an electric field to plates above and below.

Phosphor persistence

Various phosphors are available depending upon the needs of the measurement or display application. The brightness, color, and persistence of the illumination depends upon the type of phosphor used on the CRT screen. Phosphors are available with persistences ranging from less than one microsecond to several seconds. For visual observation of brief transient events, a long persistence phosphor may be desirable. For events which are fast and repetitive, or high frequency, a short-persistence phosphor is generally preferable.

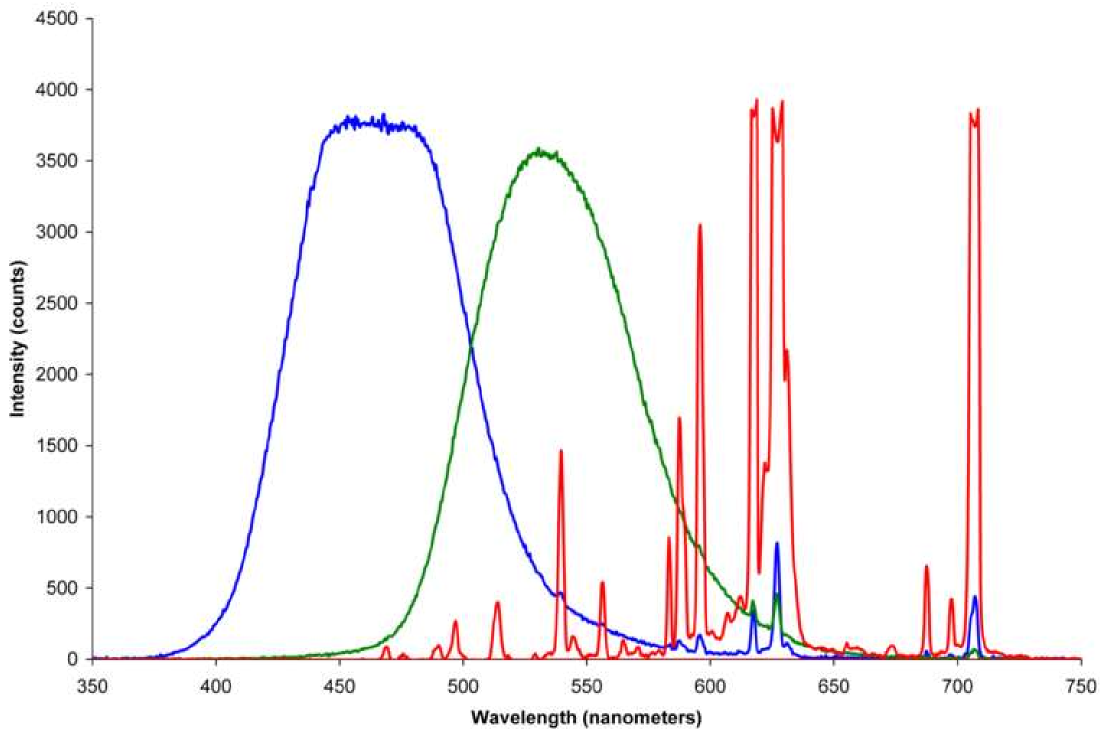
Microchannel plate

When displaying fast one-shot events the electron beam must deflect very quickly, with few electrons impinging on the screen; leading to a faint or invisible image on the display. Oscilloscope CRTs designed for very fast signals can give a brighter display by passing the electron beam through a micro-channel plate just before it reaches the screen. Through the phenomenon of secondary emission this plate multiplies the number of electrons reaching the phosphor screen, giving a significant improvement in writing rate (brightness), and improved sensitivity and spot size as well.

Graticules

Most oscilloscopes have a graticule as part of the visual display, to facilitate measurements. The graticule may be permanently marked inside the face of the CRT, or it may be a transparent external plate. External graticules are typically made of glass or acrylic plastic. An internal graticule provides an advantage in that it eliminates parallax error. Unlike an external graticule, an internal graticule can not be changed to accommodate different types of measurements. Oscilloscopes commonly provide a means for the graticule to be side-illuminated, which improves its visibility when used in a darkened room or when shaded by a camera hood.

Color CRTs



Spectra of constituent blue, green and red phosphors in a common CRT

Color tubes use three different phosphors which emit red, green, and blue light respectively. They are packed together in stripes (as in aperture grille designs) or clusters called "triads" (as in shadow mask CRTs). Color CRTs have three electron guns, one for each primary color, arranged either in a straight line or in a triangular configuration (the guns are usually constructed as a single unit). A grille or mask absorbs the electrons that would otherwise hit the wrong phosphor. A shadow mask tube uses a metal plate with tiny holes, placed so that the electron beam only illuminates the correct phosphors on the face of the tube. Another type of color CRT uses an aperture grille to achieve the same result.

Convergence in color CRTs

The three beams in color CRTs would not strike the screen at the same point without convergence calibration. Instead, the set would need to be manually adjusted to converge the three color beams together to maintain color accuracy.

Degaussing

Most CRT television sets and computer monitors have a built-in degaussing (demagnetizing) coil, which upon power-up creates a brief, alternating magnetic field which decays in strength over the course of a few seconds. This degaussing field is strong enough to remove most cases of shadow mask magnetization.

Vector monitors

Vector monitors were used in early computer aided design systems and in some late-1970s to mid-1980s arcade games such as *Asteroids*. They draw graphics point-to-point, rather than scanning a raster.

CRT resolution

Dot pitch defines the maximum resolution of the display, assuming delta-gun CRTs. In these, as the scanned resolution approaches the dot pitch resolution, moiré appears, as the detail being displayed is finer than what the shadow mask can render. Aperture grille monitors do not suffer from vertical moiré, however, because their phosphor stripes have no vertical detail. In smaller CRTs, these strips maintain position by themselves, but larger aperture grille CRTs require one or two crosswise (horizontal) support strips.

Gamma

CRTs have a pronounced triode characteristic, which results in significant gamma (a nonlinear relationship in an electron gun between applied video voltage and light intensity).

Other types of CRTs

Cat's eye

In better quality tube radio sets a tuning guide consisting of a phosphor tube was used to aid the tuning adjustment. This was also known as a "Magic Eye" or "Tuning Eye". Tuning would be adjusted until the width of a radial shadow was minimized. This was used instead of a more expensive electromechanical meter, which later came to be used on higher-end tuners when transistor sets lacked the high voltage required to drive the device.

Charactrons

Some displays for early computers (those that needed to display more text than was practical using vectors, or that required high speed for photographic output) used Charactron CRTs. These incorporate a perforated metal character mask (stencil), which shapes a wide electron beam to form a character on the screen. The system selects a character on the mask using one set of deflection circuits, but that causes the extruded beam to be aimed off-axis, so a second set of deflection plates has to re-aim the beam so it is headed toward the center of the screen. A third set of plates places the character wherever required. The beam is unblanked (turned on) briefly to draw the character at that position. Graphics could be drawn by selecting the position on the mask corresponding to the code for a space (in practice, they were simply not drawn), which had a small round hole in the center; this effectively disabled the character mask, and the system reverted to regular vector behavior. Charactrons had exceptionally-long necks, because of the need for three deflection systems.

Nimo

Nimo tube BA0000-P31

Nimo was the trademark of a family of small specialised CRTs manufactured by Industrial Electronics Engineers. These had 10 electron guns which produced electron beams in the form of digits in a manner similar to that of the charactron. The tubes were either simple single-digit displays or more complex 4- or 6- digit displays produced by means of a suitable magnetic deflection system. Having little of the complexities of a standard CRT, the tube required a relatively simple driving circuit, and as the image was projected on the glass face, it provided a much wider viewing angle than competitive types (e.g. nixie tubes).

Zeus Thin CRT Displays

In the late 1990s and early 2000s Philips Research Laboratories experimented with a type of thin CRT known as the *Zeus* display which contained CRT-like functionality in a flat panel. The devices were demonstrated but never marketed.

The future of CRT technology

Demise

Although a mainstay of display technology for decades, the demand for CRT screens has dropped precipitously since 2000, and this falloff has been accelerating in the latter half of that decade. The rapid advances and falling prices of LCD flat panel technology, first for computer monitors and then for televisions, has been the key factor in the demise of competing display technologies such as CRT, rear-projection, and plasma display.

The end of most high-end CRT production by around 2010 (including high-end Sony and Mitsubishi product lines) means an erosion of the CRT's capability. In Canada and the United States, the sale and production of high-end CRT TVs (30-inch screens) in these markets has all but ended by 2007; just a couple years later inexpensive combo CRT TVs (20-inch screens with an integrated VHS or DVD player) have disappeared from discount stores. It has been common to replace CRT-based televisions and monitors in as little as 5–6 years, although they generally are capable of satisfactory performance for a much longer time.

Companies are responding to this trend. Electronics retailers such as Best Buy have been steadily reducing store spaces for CRTs. In 2005, Sony announced that they would stop the production of CRT computer displays. Samsung did not introduce any CRT models for the 2008 model year at the 2008 Consumer Electronics Show and on February 4, 2008 Samsung removed their 30" wide screen CRTs from their North American website and has not replaced them with new models.

The demise of CRT, however, has been happening more slowly in the developing world. According to iSupply, production in units of CRTs was not surpassed by LCDs production until 4Q 2007, owing largely to CRT production at factories in China.

In the United Kingdom, DSG (Dixons), the largest retailer of domestic electronic equipment, reported that CRT models made up 80–90% of the volume of televisions sold at Christmas 2004 and 15–20% a year later, and that they were expected to be less than 5% at the end of 2006. Dixons ceased selling CRT televisions in 2007.

Causes

CRTs, despite recent advances, have remained relatively heavy and bulky and take up a lot of space in comparison to other display technologies. CRT screens have much deeper cabinets compared to flat panels and rear-projection displays for a given screen size, and so it becomes impractical to have CRTs larger than 40 inches (102 cm). The CRT disadvantages became especially significant in light of rapid technological advancements in LCD and plasma flat-panels which allow them to easily surpass 40 inches (102 cm) as well as being thin and wall-mountable, two key features that were increasingly being demanded by consumers.

By 2006, although the price points of CRTs are generally much lower than LCD and plasma flat panels, large screen CRTs (30-inches or more) are as expensive as a similar-sized LCD. While LCDs are generally the most expensive TV display technology, major innovations have caused prices to drop significantly.

Monochrome CRTs are even more efficient than color CRTs. This is because up to 2/3rds of the backlight power of LCD and rear-projection displays are lost to the RGB stripe filter. Most LCDs also have poorer color rendition and can change color with viewing angle, though modern PVA and IPS LCDs have greatly attenuated these problems.

Resurgence in specialized markets

In the first quarter of 2008, CRTs retook the #2 technology position in North America from plasma, due to the decline and consolidation of plasma display manufacturers. DisplaySearch has reported that although in the 4Q of 2007 LCDs surpassed CRTs in worldwide sales, CRTs then outsold LCDs in the 1Q of 2008.

CRTs are useful for displaying photos with high pixels per unit area and correct color balance. LCDs, as currently the most common flatscreen technology, have generally inferior color rendition (despite having greater overall brightness) due to the fluorescent lights commonly used as a backlight.

CRTs are still popular in the printing and broadcasting industries as well as in the professional video, photography, and graphics fields due to their greater color fidelity, contrast, and better viewing from off-axis (wider viewing angle). CRTs also still find adherents in video gaming because of their higher resolution per initial cost, fast response time, and multiple native resolutions.

Health concerns

Ionizing radiation

CRTs can emit a small amount of X-ray radiation as a result of the electron beam's bombardment of the shadow mask/aperture grille and phosphors. The amount of radiation escaping the front of the monitor is widely considered unharmful. The Food and Drug Administration regulations in 21 C.F.R. 1020.10 are used to strictly limit, for instance, television receivers to 0.5 milliroentgens per hour (mR/h) (0.13 µC/(kg·h) or 36 pA/kg) at a distance of 5 cm (2 in) from any external surface; since 2007, most CRTs have emissions that fall well below this limit.

Toxicity

Color and monochrome CRTs may contain toxic substances, such as cadmium, in the phosphors. The rear glass tube of modern CRTs may be made from leaded glass, which represent an environmental hazard if disposed of improperly. By the time personal computers were produced, glass in the front panel (the viewable portion of the CRT) used barium rather than lead, though the rear of the CRT was still produced from leaded glass. Monochrome CRTs typically do not contain enough leaded glass to fail EPA tests.

In October 2001, the United States Environmental Protection Agency created rules stating that CRTs must be brought to special recycling facilities. In November 2002, the EPA began fining companies that disposed of CRTs through landfills or incineration. Regulatory agencies, local and statewide, monitor the disposal of CRTs and other computer equipment.

In Europe, disposal of CRT televisions and monitors is covered by the WEEE Directive.

Flicker

At low refresh rates (below 50 Hz), the periodic scanning of the display may produce an irritating flicker that some people perceive more easily than others, especially when viewed with peripheral vision. A high refresh rate (above 72 Hz) reduces the effect. Computer displays and televisions with CRTs driven by digital electronics often use refresh rates of 100 Hz or more to largely eliminate any perception of flicker. Non-computer CRTs or CRT for sonar or radar may have long persistence phosphor and are thus flicker free. If the persistence is too long on a video display, moving images will be blurred.

High-frequency noise

CRTs used for television operate with horizontal scanning frequencies of 15,734 Hz (for NTSC systems) or 15,625 Hz (for PAL systems). These frequencies are at the upper range of human hearing and are inaudible to many people; some people will perceive a high-pitched tone near an operating television CRT. The sound is due to magnetostriction in the magnetic core of the flyback transformer.

Implosion

A high vacuum exists within all cathode ray tubes, putting the envelope under relatively high stress. If the outer glass envelope is damaged, the glass will break and pieces will fly out at high speed. While modern Cathode Ray Tubes used in televisions and computer displays have epoxy-bonded face-plates or other measures to prevent shattering of the envelope, CRTs removed from equipment must be handled carefully to avoid personal injury.

Security concerns

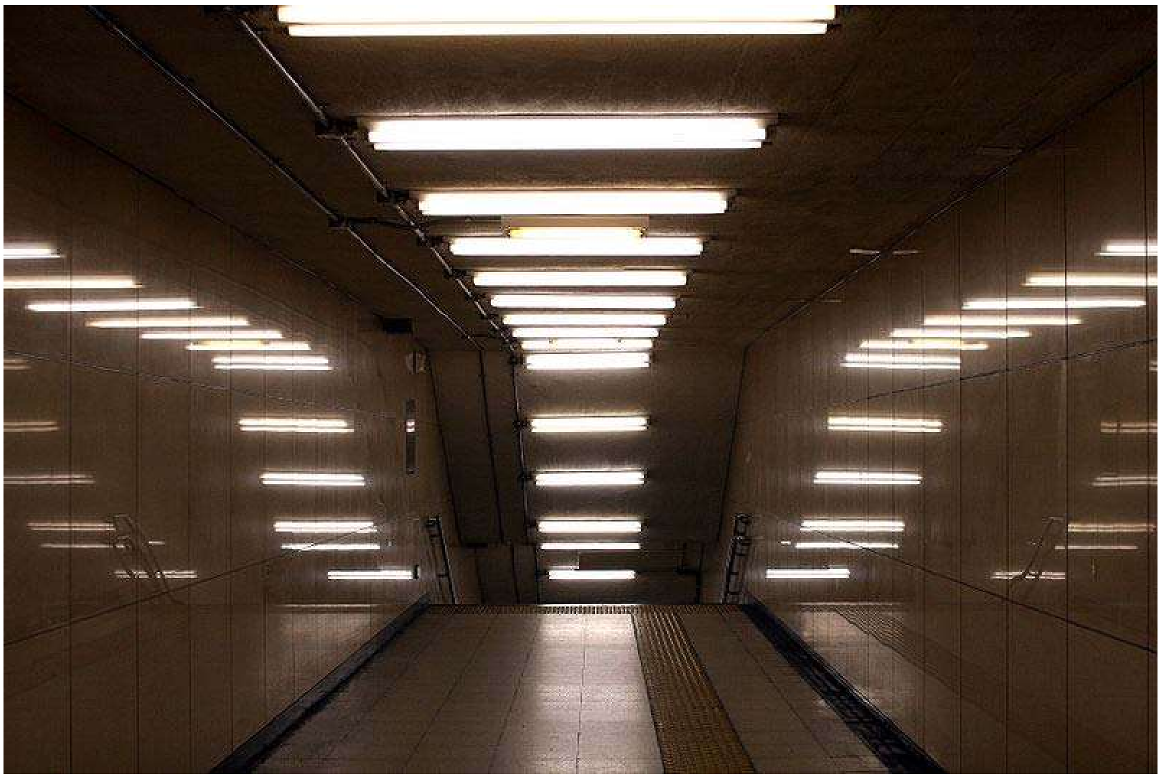
Under some circumstances, the signal radiated from the electron guns, scanning circuitry, and associated wiring of a CRT can be captured and used to remotely reconstruct what is shown on the CRT, using a process called Van Eck phreaking. Special TEMPEST shielding can mitigate this effect. Such radiation of a potentially exploitable signal however occurs also with LCDs and with all electronics in general.

Recycling

CRTs are considered a type of electronic waste, but are generally regarded as one of the hardest type to recycle. The main problems associated with the disposal of a CRT come from their relatively high concentration of lead and phosphorus, both of which are necessary for the display. There are several companies in the United States that charge a small fee to collect CRTs, then subsidize their labor by selling the harvested copper, wire, and printed circuit boards. Leaded CRT glass is sold to get remelted into other CRTs, or even broken down and used in road construction.

Chapter- 3

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.

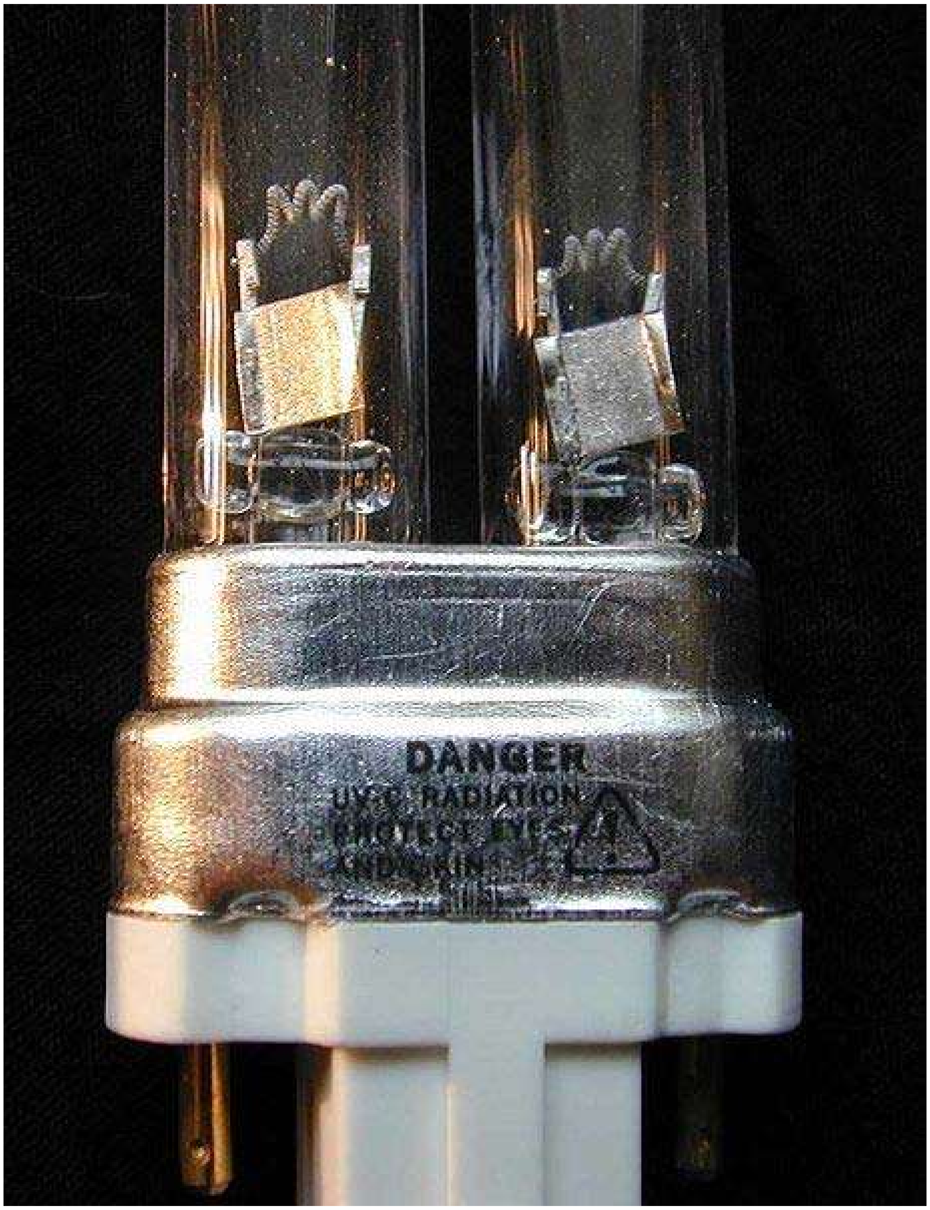
Principles of operation

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.

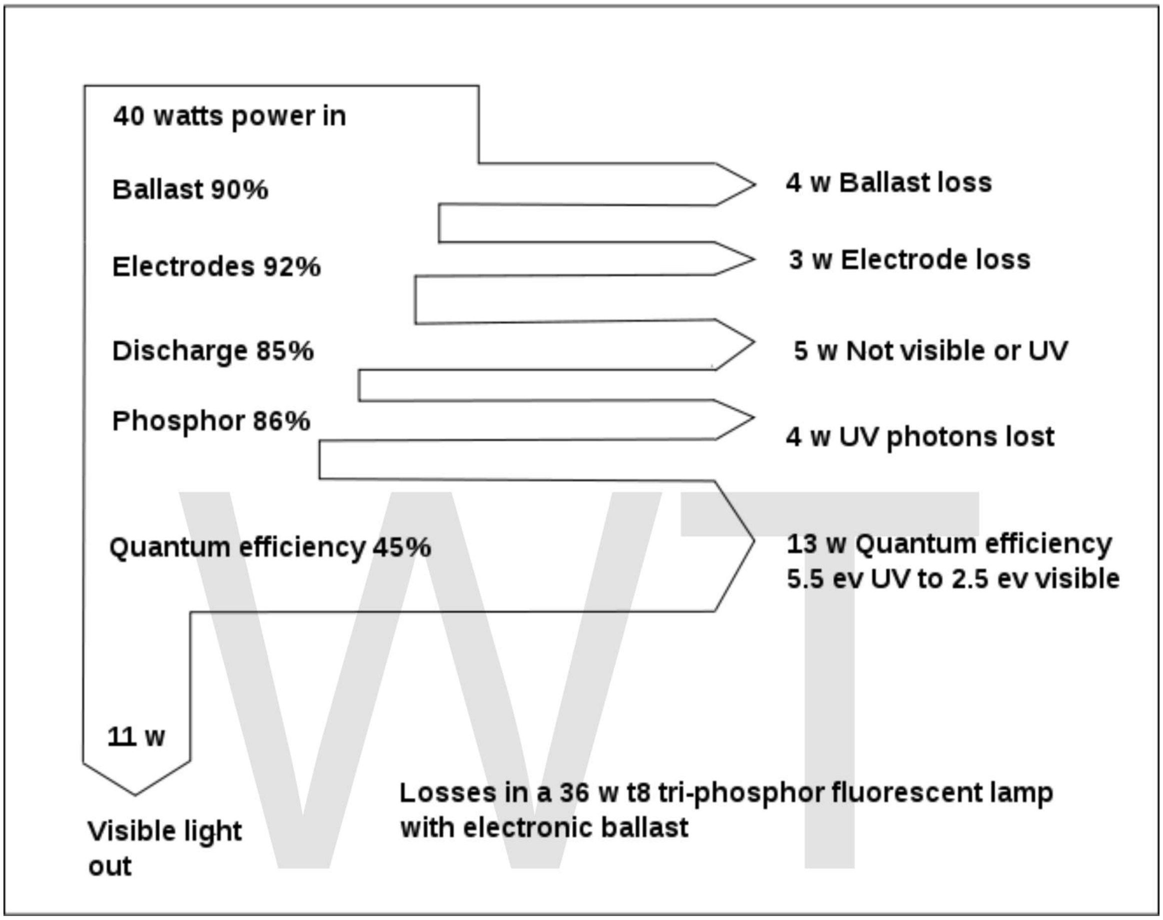
Fluorescent lamps can run directly from a DC supply of sufficient voltage to strike an arc. The ballast must be resistive, and would consume about as much power as the lamp. When operated from DC, the starting switch is often arranged to reverse the polarity of the supply to the lamp each time it is 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.

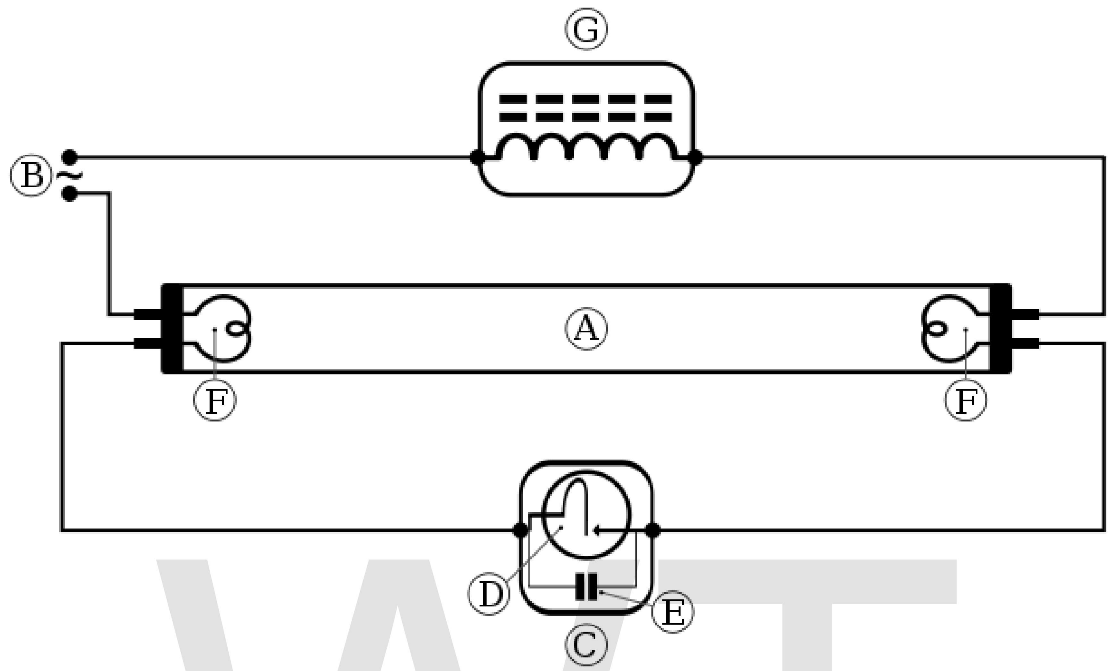
Cold cathode lamps

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).

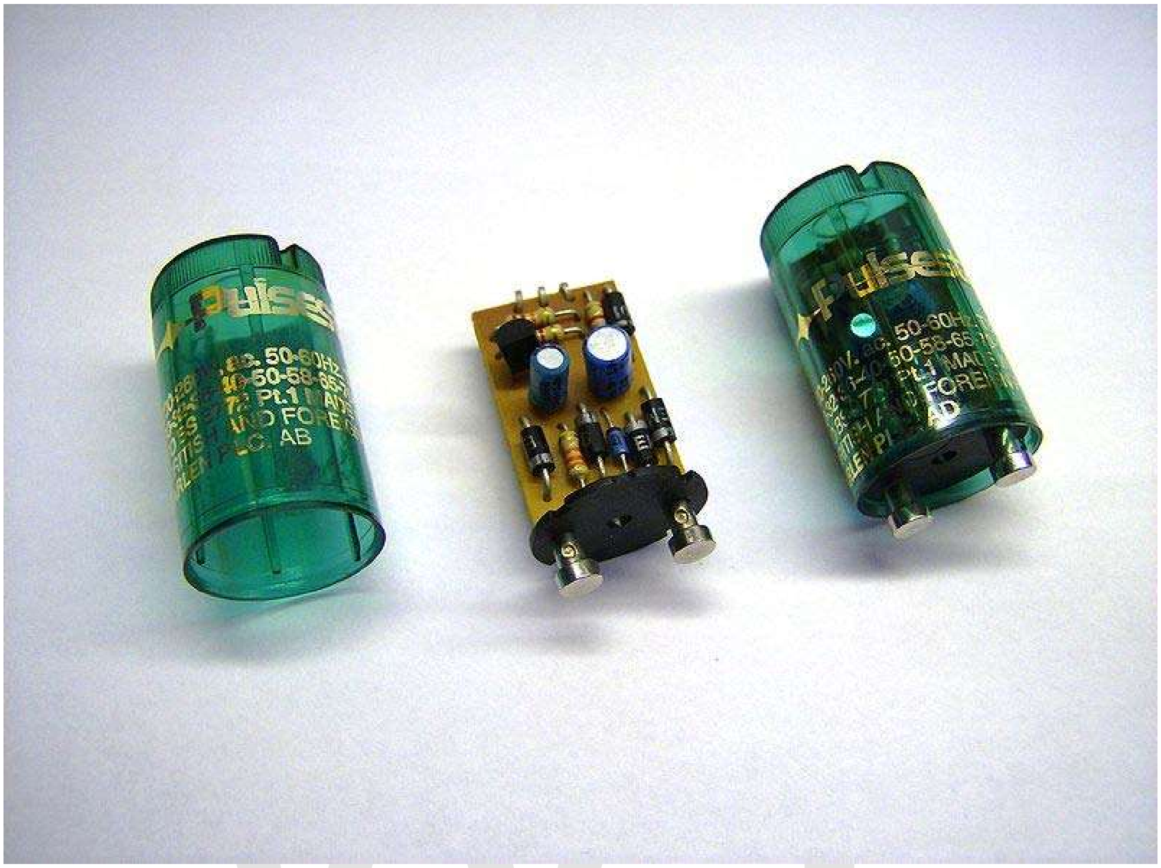
Switchstart/preheat

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.

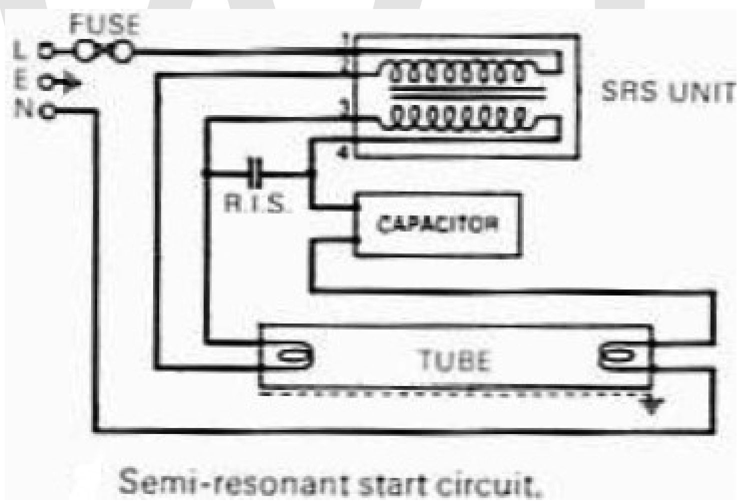
A rapid-start "iron" (magnetic) ballast continually heats the cathodes at the ends of the lamps. This ballast runs two F40T12 lamps in series.

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.

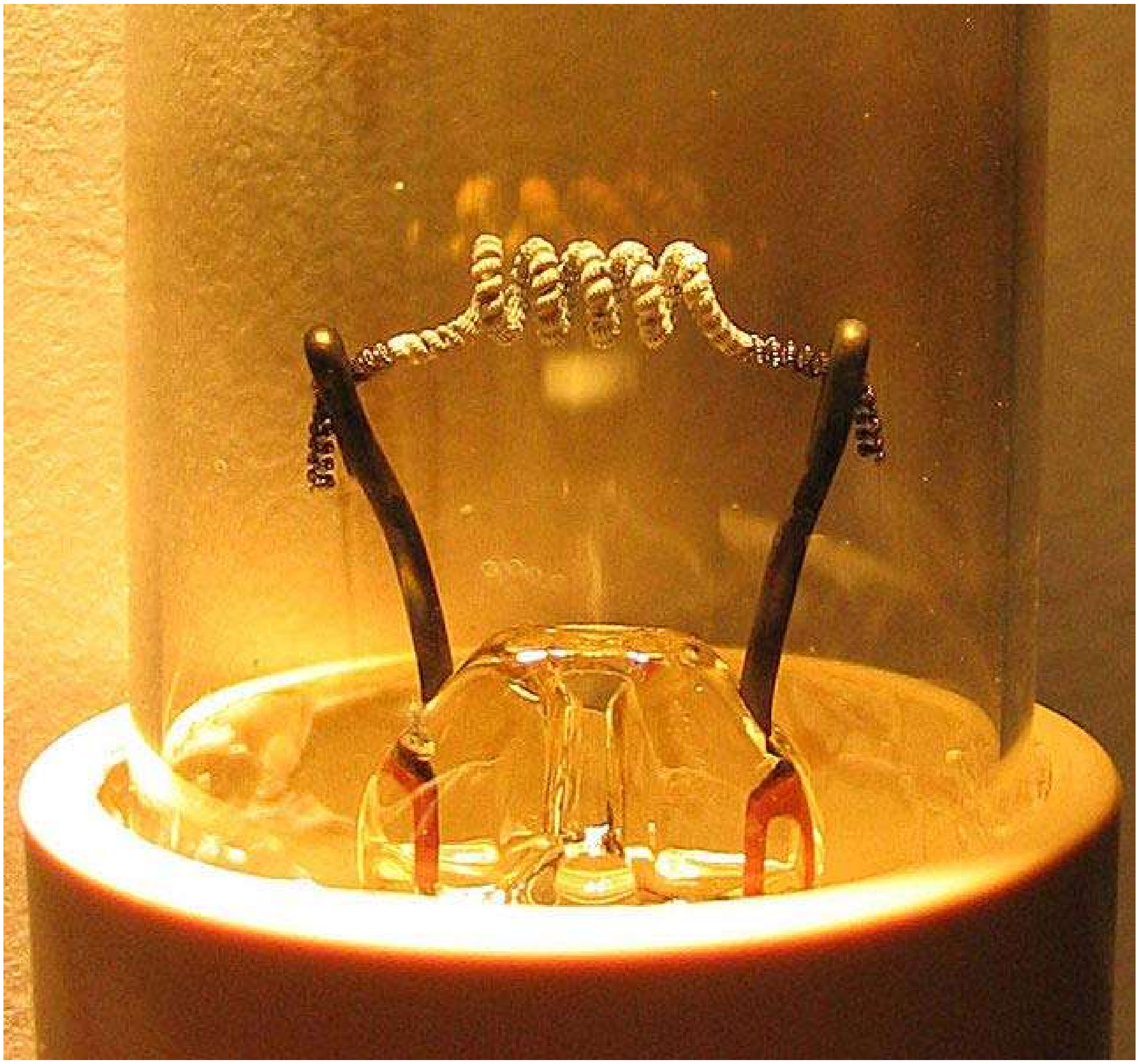
Many electronic ballasts are controlled by a microcontroller or similar, and these are sometimes called digital ballasts. Digital ballasts can apply quite complex logic to lamp starting and operation. This enables functions such as testing for broken electrodes and missing tubes before attempting to 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

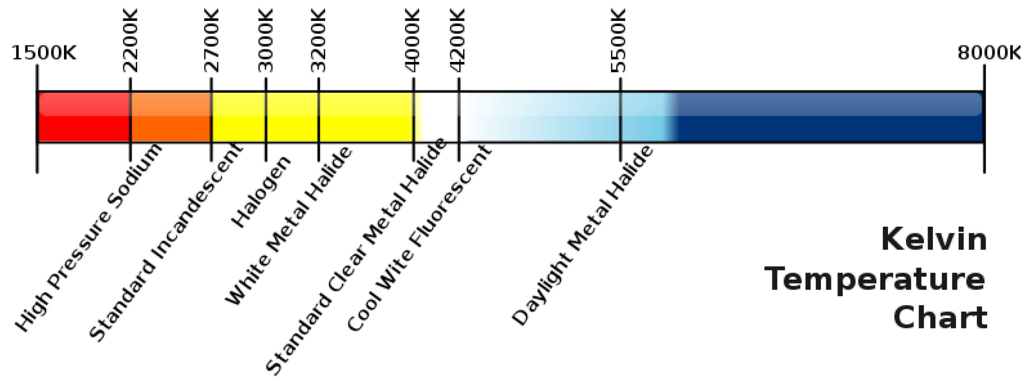
The filaments can burn at the end of the lamp's lifetime, opening the circuit and losing the capability to heat up. Both filaments lose function as they are connected in series, with just a simple switch start circuit a broken filament will render the lamp completely useless. Filaments rarely burn or 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.

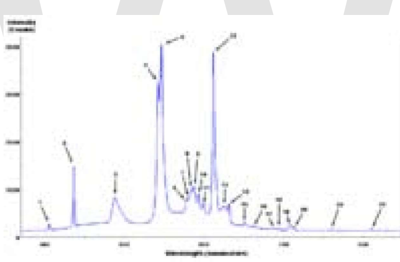
Phosphor composition

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.

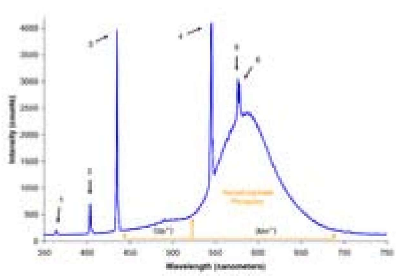
Fluorescent lamp spectra

Typical fluorescent lamp with "rare earth" phosphor



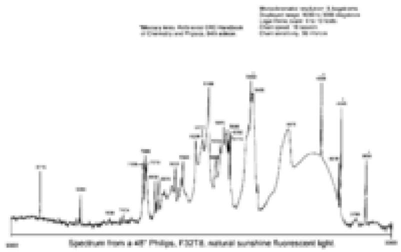
A typical "cool white" fluorescent lamp utilizing two rare earth doped phosphors, $Tb^{3+}, Ce^{3+}:LaPO_4$ for green and blue emission and $Eu:Y_2O_3$ for red. Note that several of the spectral peaks are directly generated from the mercury arc. This is likely the most common type of fluorescent lamp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

An older style halophosphate phosphor fluorescent lamp



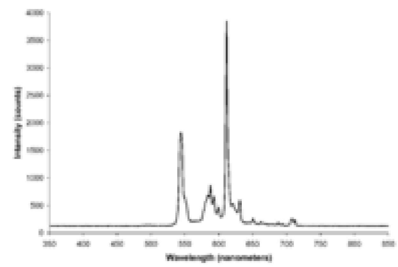
Halophosphate phosphors in these lamps usually consist of trivalent antimony and divalent manganese doped calcium halophosphate ($Ca_5(PO_4)_3(Cl, F):Sb^{3+}, Mn^{2+}$). The color of the light output can be adjusted by altering the ratio of the blue emitting antimony dopant and orange emitting manganese 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



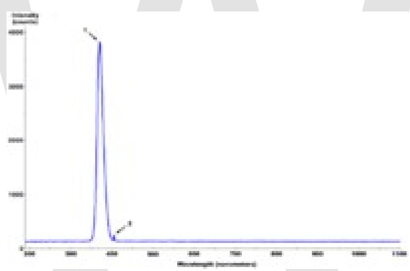
An explanation of the origin of the peaks is on the image page.

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.

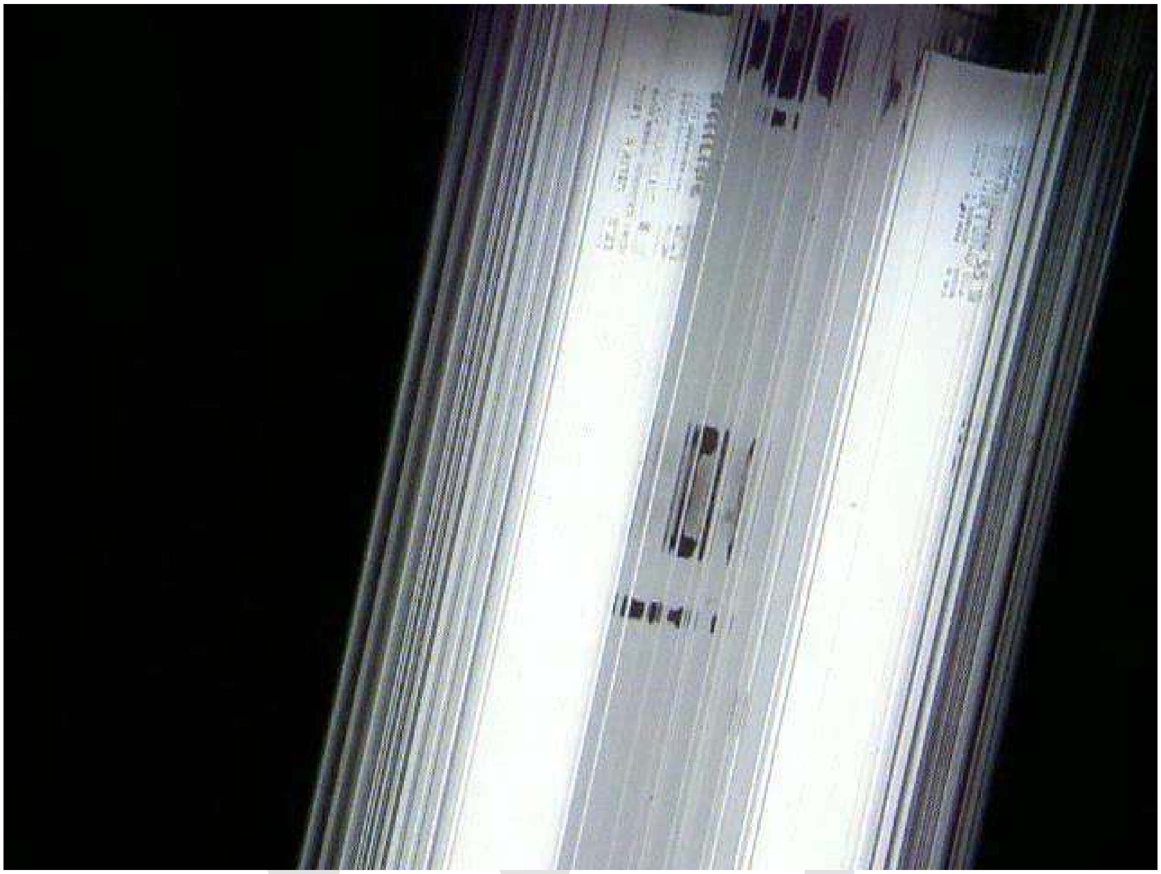
The compact fluorescent lamp (CFL) replaces regular incandescent bulbs. However, some CFLs will not fit some lamps, because the harp (heavy wire shade support bracket) is shaped for the narrow neck of an incandescent lamp, while CFLs tend to have a wide housing for their electronic ballast close to the 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- 4

LED Lamp

An **LED lamp** is a solid-state lamp that uses light-emitting diodes (LEDs) as the source of light. The term *LED lightbulb* is also colloquially used. *LED lamp* may in general refer to conventional semiconductor light-emitting diodes, to organic LEDs (OLED), or polymer light-emitting diodes (PLED) devices, although OLED and PLED technologies are not commercially available in 2010.

Since the light output of individual light-emitting diodes is small compared to incandescent and compact fluorescent lamps, multiple diodes are often used together. In recent years, as diode technology has improved, high power light-emitting diodes with higher lumen output are making it possible to replace other lamps with LED lamps. One high power LED chip used in some commercial LED lights can emit 7,527 lumens while using only 100 watts. LED lamps can be made interchangeable with other types of lamps.

Diodes use direct current (DC) electrical power, so LED lamps must also include internal circuits to operate from standard AC voltage. LEDs are damaged by being run at higher temperatures, so LED lamps typically include heat management elements such as heat sinks and cooling fins. LED lamps offer long service life and high energy efficiency, but initial costs are higher than those of fluorescent lamps.

An assortment of LED lightbulbs that are commercially available as of 2010 as replacements for screw-in bulbs, including floodlight fixtures (left), reading light (center), household lamps (center right and bottom), and low-power accent light (right) applications.

Technology overview

Dropped ceiling with LED lamps

General purpose lighting needs white light. LEDs emit light in a very small band of wavelengths, emitting strongly colored light. The color is characteristic of the energy bandgap of the semiconductor material used to make the LED. To emit white light from LEDs requires either mixing light from red, green, and blue LEDs, or using a phosphor to convert some of the light to other colors.

The first method (RGB-LEDs) uses multiple LED chips each emitting a different wavelength in close proximity, to form the broad white light spectrum. The advantage of this method is that the intensity of each LED can be adjusted to "tune" the character of the light emitted. The major disadvantage is high production cost.

The second method, phosphor converted LEDs (pcLEDs) uses one short wavelength LED (usually blue or ultraviolet) in combination with a phosphor, which absorbs a portion of the blue light and emits a broader spectrum of white light. (The mechanism is similar to the way a fluorescent lamp emits white light from a UV-illuminated phosphor.) The major advantage here is the low production cost, and high CRI (color rendering index), while the disadvantage is the inability to dynamically change the character of the light and the fact that phosphor conversion reduces the efficiency of the device. The low cost and adequate performance makes it the most widely used technology for general lighting today.

A single LED is a low-voltage solid state device and cannot be directly operated on standard AC current without some circuitry to control the voltage applied and the current flow through the lamp. A series diode and resistor could be used to control the voltage polarity and to limit the current, but this is inefficient since most of the applied voltage would be dropped as wasted heat in the resistor. A single series string of LEDs would minimize dropped-voltage losses, but one LED failure could extinguish the whole string. Paralleled strings increase reliability by providing redundancy. In practice, three strings or more are usually used. To be useful for illumination for home or work spaces, a number of LEDs must be placed close together in a lamp to combine their illuminating effects. This is because individual LEDs emit only a fraction of the light of traditional light sources. When using the color-mixing method, a uniform color distribution can be difficult to achieve, while the arrangement of white LEDs is not critical for color balance. Further, degradation of different LEDs at various times in a color-mixed lamp can lead to an uneven color output. LED lamps usually consist of clusters of LEDs in a housing with both driver electronics, a heat sink and optics.

Application

LED lamps are used for both general and special-purpose lighting. Where colored light is needed, LEDs come in multiple colors, which are emitted with no need for filters. This improves the energy efficiency over a white light source that generates all colors of light then discards some of the visible energy in a filter.

Compared to fluorescent bulbs, advantages claimed for LED light bulbs are that they contain no mercury (unlike a Compact fluorescent lamp or CFL), that they turn on instantly, and that lifetime is unaffected by cycling on and off, so that they are well suited for light fixtures where bulbs are often turned on and off. LED light bulbs are also less apt to break.

White-light light-emitting diode lamps have the traits of long life expectancy and relatively low energy use. The LED sources are compact, which gives flexibility in designing lighting fixtures and good control over the distribution of light with small reflectors or lenses. Because of the small size of LEDs, control of the spatial distribution of illumination is extremely flexible, and the light output and spatial distribution of a LED array can be controlled with no efficiency loss.

LED lamps have no glass tubes to break, and their internal parts are rigidly supported, making them resistant to vibration and impact. With proper driver electronics design, an LED lamp can be made dimmable over a wide range; there is no minimum current needed to sustain lamp operation.

LEDs using the color-mixing principle can emit a wide range of colors by changing the proportions of light generated in each primary color. This allows full color mixing in lamps with LEDs of different colors. In contrast to other lighting technologies, LED emission tends to be directional (or at least lambertian). This can be either an advantage or a disadvantage, depending on the requirements of the application. For applications where non-directional light is required, either a diffuser is used, or multiple individual LED emitters are used to cover different directions.

Household LED lamps

LED Lamp with E27 Edison screw, interchangeable with incandescent lamps

Lamp sizes and bases

LED lamps intended to be interchangeable with incandescent lamps are made in standard light bulb shapes, such as an Edison screw base, an MR16 shape with a bi-pin base, or a GU5.3 (Bipin cap) or GU10 (bayonet socket). LED lamps are made in low voltage (typically 12 V halogen-like) varieties, and as replacements for regular AC (e.g. 120 or 240 V AC) lighting. These lamps typically include circuitry to rectify the AC power and to convert the voltage to a level usable by the internal LED elements.

LED light bulbs

Many LED lamps have become available as replacements for screw-in incandescent or compact fluorescent light bulbs, ranging from low-power 5–40 watt incandescent bulbs, through conventional replacement bulbs for 60 watt incandescent bulbs (typically requiring about 7 watts of power), and as of 2010 a few lamps were available to replace higher wattage bulbs, e.g., a 13-watt LED bulb which is about as bright as a 100W incandescent. (A standard general purpose incandescent bulb emits light at an efficiency of about 14 to 17 lumens/W depending on its size and voltage. According to the European Union standard, an energy-efficient bulb that claims to be the equivalent of a 60W tungsten bulb must have a minimum light output of 806 lumens.)

Most LED bulbs are not designed to be dimmed (although some models are designed to work with dimmers), and are usually directional. The lamps have declined in cost to between US$30 to $50 each as of 2010. These bulbs are more power-efficient than compact fluorescent bulbs and offer lifespans of 30,000 or more hours, reduced operated at a higher temperature than specified. Incandescent bulbs have a typical life of 1,000 hours, compact fluorescents about 8,000 hours. A LED light bulb can be expected to last 25–30 years under normal use. The bulbs maintain output light intensity very well over their life-times. Energy Star specifications require the bulbs to typically drop less than 10% after 6000 or more hours of operation, and in the worst case not more than 15%. They are also mercury free, unlike fluorescent lamps. LED lamps are available with a variety of color properties. The higher purchase cost than other types may be more than offset by savings in energy and maintenance.

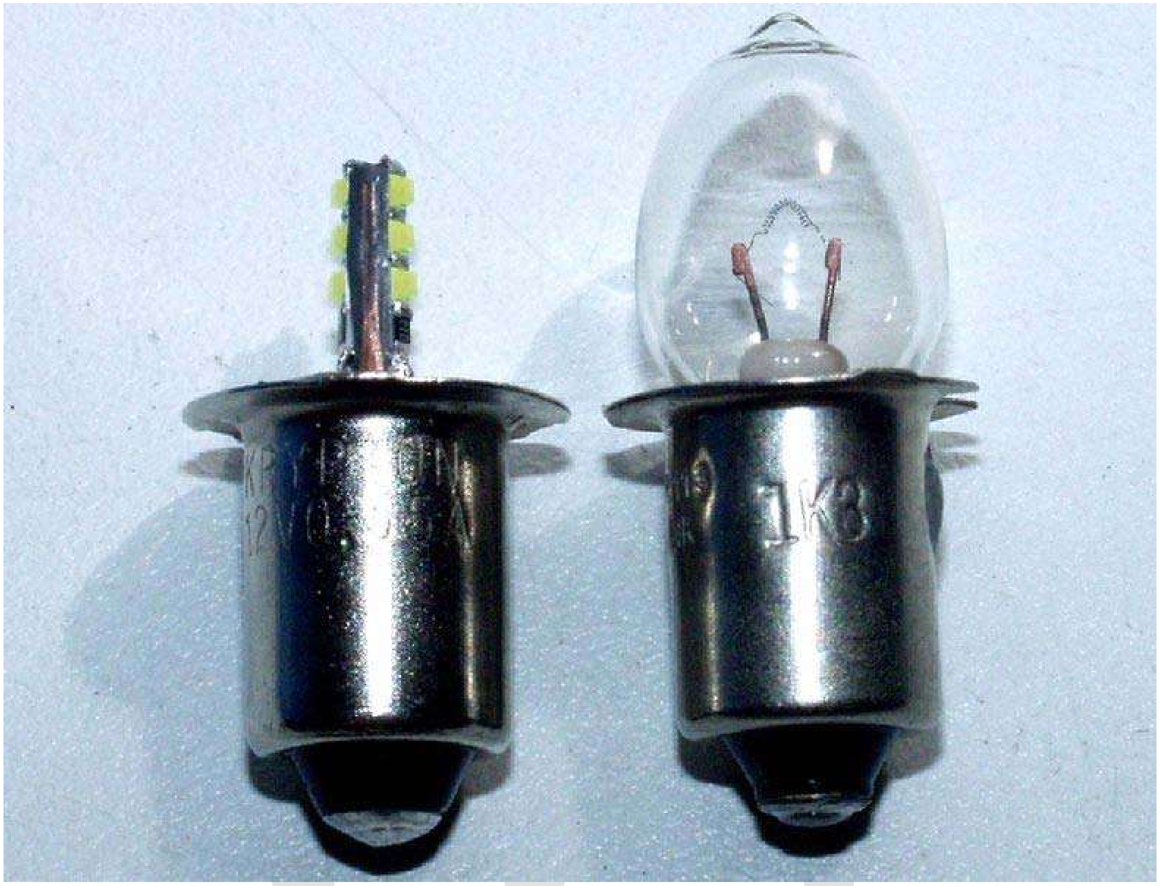
Several companies offer LED lamps for general lighting purposes. The C. Crane Company introduced a 7-watt replacement for a 60-watt bulb, the "Geobulb", with an efficiency of 59 lumens/W. The company also offers wedge-base lamps for replacement in low voltage fixtures. In the Netherlands, a company called Lemnis Lighting offers a dimmable LED lamp called Pharox. The company Eternleds Inc. offers a bulb called HydraLux-4 which uses liquid cooling of the LED chips. Philips makes a number of LED lamps which are commercially available in the United States and come with a six year warranty, and a number of smaller producers can be found that sell LED lights that are screw-in replacements for conventional bulbs, for example, the General LED Bulb from Arani

LED tubes in various length

The technology is improving rapidly, and new energy-efficient consumer LED lamps have been announced from three of the lighting industry's largest producers, Osram Sylvania, Philips, and General Electric, so these listings should be taken as not necessarily representative of what is currently available.

High power LED lamp with GU5.3 fitting and aluminum heat sink, intended to replace halogen reflector lamps.

Specialty uses



LED Flashlight replacement bulb (left), with tungsten equivalent (right)

White LED lamps have achieved market dominance in applications where high efficiency is important at low power levels. Some of these applications include flashlights, solar-powered garden or walkway lights, and bicycle lights. Monochromatic (colored) LED lamps are now commercially used for traffic signal lamps, where the ability to emit bright monochromatic light is a desired feature, and in strings of holiday lights.

LED lights have also become very popular in gardening and agriculture by 2010. First used by NASA to grow plants in space, LEDs came into use for home and commercial applications for indoor horticulture (aka grow lights). The wavelengths of light emitted from LED lamps have been specifically tailored to supply light in the spectral range needed for chlorophyll absorption in plants, promoting growth while reducing wastage of energy by emitting minimal light at wavelengths that plants do not require. The red and blue wavelengths of the visible light spectrum are used for photosynthesis, so these are the colors almost always used in LED grow light panels. These lights are attractive to indoor growers since they use less power than other types for the same light intensity, need no ballasts, and emit much less heat than HID lamps. The reduction in heat allows time between watering cycles to be extended because the plants transpire less under LED grow lights. Due to this change in growth conditions, users of LEDs are advised not to over-water the plants.

Pioneering mass use

In 2008 Sentry Equipment Corporation in Oconomowoc, Wisconsin, USA, was able to light its new factory interior and exterior almost solely with LEDs. Initial cost was three times more than a traditional mix of incandescent and fluorescent lamps, but the extra cost will be repaid within two years via electricity savings, and the lamps should not need replacing for 20 years. In 2009, the Manapakkam, Chennai office of the Indian IT company iGate spent 3,700,000 Indian rupees (U$80,000) to light 57,000 sq ft (5,300 m^2) of office space with LEDs. The firm expects the new lighting to pay for itself fully within 5 years.

LEDs on a big Christmas tree

In 2009 the exceptionally big Christmas tree standing in front of the Turku Cathedral in Finland was hung with 710 LED bulbs, each using 2 watts. It has been calculated that these LED lamps will pay for themselves in three and a half years, even though the lights run for only 48 days per year.

By 2010 mass installations of LED lighting for commercial and public uses were becoming common.

In 2010, on the reconstructed section of Bulevar Kralja Aleksandra (King Aleksandar Boulevard) in Belgrade, Serbia, LED lamps were introduced for new street lighting.

LED lamps have also been used for a number of demonstration projects for outdoor lighting and street lights. The United States Department of Energy has available several reports on the results of many pilot projects for municipal outdoor lighting. Many additional streetlight and municipal outdoor lighting projects have been announced.

Comparison to other lighting technologies

- Incandescent lamps (light bulbs) generate light by passing electric current through a resistive filament, thereby heating the filament to a very high temperature so that it glows and emits visible light. A broad range of visible frequencies are naturally produced, yielding a "warm" yellow or white color quality. Incandescent light is highly inefficient, as about 98% of the energy input is emitted as heat. A 100 W light bulb emits about 1,700 lumens, about 17 lumens/W. Incandescent lamps are relatively inexpensive to make. The typical lifespan of an AC incandescent lamp is around 1,000 hours. They work well with dimmers. Most older light fixtures are designed for the size and shape of these traditional bulbs.

- Fluorescent lamps (light bulbs) work by passing electricity through mercury vapor, which in turn emits ultraviolet light. The ultraviolet light is then absorbed by a phosphor coating inside the lamp, causing it to glow, or fluoresce. While the heat generated by a fluorescent lamp is much less than its incandescent counterpart, energy is still lost in generating the ultraviolet light and converting this light into visible light. If the lamp breaks, exposure to mercury can occur. Linear fluorescent lamps are typically five to six times the cost of equivalent incandescent lamps but have life spans around 10,000 and 20,000 hours. Lifetime varies from 1,200 hours to 20,000 hours for compact fluorescent lamps. Most fluorescent lamps are not compatible with dimmers. Those with "iron" ballasts flicker at 100 or 120 Hz, and are less efficient. The latest T8-sized triphosphate fluorescent lamps made by Osram, Philips, Crompton and others have a life expectancy greater than 50,000 hours, if coupled with a warm-start electronic ballast. The life expectancy depends on the number of on/off cycles, and is lower if the light is cycled often. The efficiency of these new lamps approaches 100 lumens/W. The efficiency of fluorescent tubes with modern electronic ballasts and compact fluorescents commonly ranges from 50 to 67 lumens/W. Most compact fluorescents rated at 13 W or more with integral electronic ballasts achieve about 60 lumens/W, comparable to the LED bulb.

Research and development

US Department of Energy

In May 2008, the U. S. Department of Energy (DOE) announced details of the Bright Tomorrow Lighting Prize competition. The L Prize is the first government-sponsored technology competition designed to spur lighting producers to develop high quality, high efficiency solid-state lighting products to replace the common light bulb. The competition will award cash prizes, and may also lead to opportunities for federal purchasing agreements, utility programs, and other incentives for winning products.

The Energy Independence and Security Act (EISA) of 2007 authorizes DOE to establish the Bright Tomorrow Lighting Prize competition. The legislation challenges industry to develop replacement technologies for the most commonly used and inefficient products, 60 W incandescent lamps and PAR 38 halogen lamps. The L Prize specifies technical requirements for these two competition categories. Lighting products meeting the competition requirements would use just 17% of the energy used by most incandescent lamps in use today. A future L Prize program announcement will call for developing a new "21st Century Lamp," as authorized in the legislation.

The EISA legislation establishes basic requirements and prize amounts for each category. The legislation authorizes up to $20 million in cash prizes. On September 24, 2009 the DOE announced that Philips was the first to submit lamps in the category to replace the standard 60 W A-19 "Swan/Edison" light bulb.

National Institute of Standards and Technology

In June 2008, scientists at the National Institute of Standards and Technology (NIST) announced the first two standards for solid-state lighting in the United States. These standards detail the color specifications of LED lamps and LED light fixtures, and the test methods that producers should use when testing these solid-state lighting products for total light output, energy use, and chromaticity or color quality.

The Illuminating Engineering Society of North America (IESNA) published a documentary **standard LM-79**, which describes the methods for testing solid-state lighting products for their light output (lumens), energy efficiency (lumens per watt) and chromaticity.

The solid-state lights being studied are intended for general illumination, but white lights used today vary greatly in chromaticity, or specific shade of white. The American National Standards Institute (ANSI) published the **standard C78.377-2008**, which specifies the recommended color ranges for solid-state lighting products using cool to warm white LEDs with various correlated color temperatures.

DOE launched the Energy Star program for solid-state lighting products in 2008. NIST scientists assisted DOE by providing research, technical details and comments for the Energy Star specifications. Energy Star certification assures consumers that products save energy and are high quality and also serves as an incentive for producers to provide energy-saving products for consumers.

Other venues

Philips Lighting has ceased research on compact fluorescents, and is devoting the bulk of its research and development budget, 5 percent of the company's global lighting revenue, to solid-state lighting.

In January 2009, it was reported that researchers at Cambridge University had developed an LED bulb that costs £2 (about $3 U.S.), is 12 times as energy efficient as a tungsten bulb, and lasts for 100,000 hours.

Remaining problems

The production process of white LEDs is complex and many aspects have room for improvement. This means that the production price of volume products is still relatively high compared to traditional light sources. The process used to deposit the active semiconductor layers of the LED is constantly improved to increase yields and production throughput. The phosphors, which are needed for their ability to emit a broader wavelength spectrum of light, problems tuning the absorption and emission, and inflexibility of form have been issues.

More apparent to the end user, however, is the color rendering index (CRI) of low quality LEDs. CRI measures a light source's ability to render colors, with 100 being the maximum. LEDs with CRI below 75 are not recommended use in indoor lighting. Better CRI LEDs are more expensive, and more research and development is needed to reduce costs.

Variations of CCT (color correlated temperature) at different viewing angles present another obstacle against widespread use of white LED. It has been shown that CCT variations can exceed 500 K. This is clearly noticeable by human observers, who normally can distinguish CCT differences of 50 to 100 K in the range from 2000 K to 6000 K, which is the range of CCT variations of daylight.

LEDs also have limited temperature tolerance and falling efficiency as component temperature rises. This limits the total LED power that can practically be fitted into lamps that physically replace existing filament and compact fluorescent types. Much research and development is invested in improving thermal traits. Thermal management of high-power LEDs is a significant factor in design of solid state lighting equipment.

The long life of solid-state lighting products, expected to be about 50 times the most common incandescent bulbs, poses a problem for bulb makers, whose current customers buy frequent replacements.

Some critics suggest that producers may over-represent the efficiency and traits of their products to sell into a rapidly growing marketplace, suggesting that consumers still need to be wary of claims made about products in this market.

Applications

This garden light can use stored solar energy because of the low power use of its LED

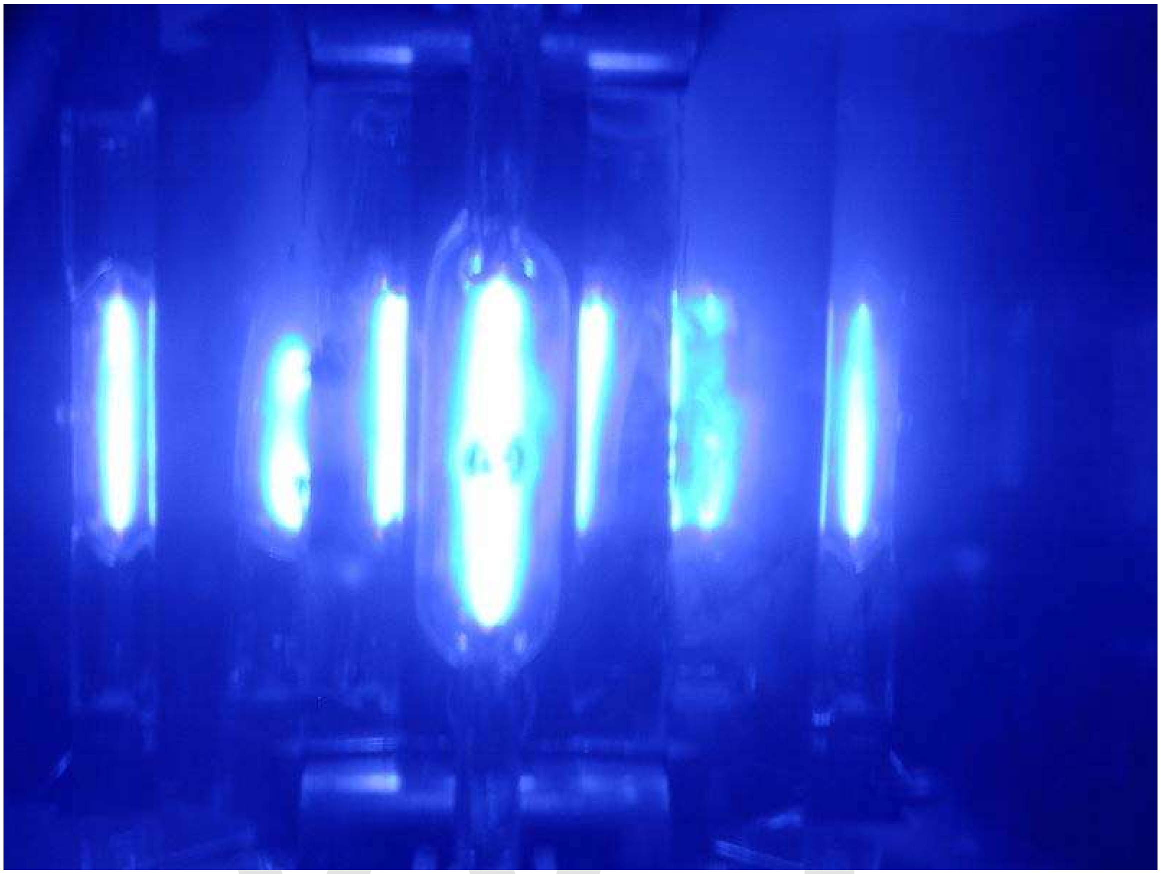
- Automotive lighting
- Bicycle lighting
- Billboard displays
- Display lighting in art galleries to reduce heating on works to low values
- Domestic lighting
- Emergency lighting
- Flashlight (Electric torches)
- Floodlighting of buildings

- Grow lights for Plants
- Public transit vehicle route and destination signs
- Railway signals
- Stage lighting
- Traffic lights
- Train lights

Chapter- 5

Tanning Lamp

Typical tanning lamp with F71T12 markings. This example is a 71 inch, bi-pin, 100 watt model, the most common.



A high pressure tanning lamp under power

Tanning lamps (sometimes called **tanning bulbs** in the United States or **tanning tubes** in Europe) are the part of a tanning bed, booth or other tanning device which produces ultraviolet light responsible for tanning. While there are literally hundreds of different kinds of tanning lamps, they can usually be classified in two basic groups: low pressure and high pressure. Within the industry, it is common to call high pressure units "bulbs" and low pressure units "lamps", although there are many exceptions and not everyone follows this example. This is likely due to the size of the unit, rather than the type. Both types require an oxygen free environment inside the lamp.

Fluorescent tanning lamps require an electrical ballast to provide power. While the resistance of an incandescent lamp filament inherently limits the current inside the lamp, tanning lamps do not and instead have negative resistance. They are plasma devices, like a neon sign, and will pass as much current as the external circuit will provide, even to the point of self destruction. Thus a ballast is needed to regulate the amount of electricity that flows through them.

The primary purpose of the tanning lamp is to create a suntan by means other than exposure to the sun. This is accomplished in a tanning bed, tanning booth, tanning canopy or free standing single bulb tanning unit. The quality of the tan (or how similar it is to a tan from the natural sun) depends upon the spectrum of the light that is generated from the lamps. Most tanning lamps produce much more UV than the sun on a typical day. This gives the user a faster base tan, but one that fades faster and offers less protection from the sun than a natural tan.

High pressure bulbs

Typical high pressure bulb. Note the small specks, which are mercury droplets. This is the more common 400W "clip in" or ceramic style.

High pressure bulbs are 3 to 5 inches long and typically powered by a ballast with 250 to 2000 watts. The most common is the 400 watt variety that is used as an added face tanner in the traditional tanning bed. High pressure lamps use quartz glass, and as such do not filter UVC. Because UVC can be deadly, a special dichroic filter glass (usually purple) is required that will filter out the UVC and UVB. The goal with high pressure tanning bulbs is to produce a high amount of UVA only. Unfiltered light from a high pressure lamp is rich in UVC used in germicidal lamps, for water purification, but it damages human skin.

The contents of a high pressure lamp are inert gas (such as argon) and mercury. There are no phosphors used, and the mercury is clearly visible if it is not in a gaseous state. During installation, even a small amount of oil from fingertips can cause the quartz envelope to fail in operation. Most commercial replacement bulbs come with a special pocket wipe, usually containing alcohol, to clean the bulb in case it is accidentally touched during installation. Because the bulb contains mercury, great care should be used if a bulb is broken, to prevent accidental contact or vapor exposure.

Low pressure lamps

While studying the beneficial effects of ultraviolet light on athletes, German scientist Friedrich Wolff noticed an interesting side effect - tanned skin. Realizing the appeal of a beautiful tan, Wolff founded the indoor tanning industry. His research led to development of indoor tanning equipment and lamp technology. Called "the father of indoor tanning," Wolff brought his European technology to the United States in 1978. He set the standard for the industry with specialized lamps and a reflector system that was ideally suited to indoor tanning. Today, the company operates in North America and Western Europe, and has patent licensees in Belgium, Canada, Germany, Sweden, Switzerland and the United States.

Low pressure lamps resemble the common fluorescent lamp used in offices everywhere. The lamps are sized by using common codes for fluorescent lamps such as **F71T12BL50BP** In this example, the F71 denotes the length, nominally 71 inches. The T12 section refers to the diameter of the lamp in 1/8th inch increments, making a T12 lamp 1.5 inches in diameter. The other numbers are optional, but commonly used, with the BL standing for a blue phosphor, the 50 indicating a 5% UVB (95% UVA) rating, and the BP indicating bi-pin ends, which all F71 lamps have. Lamps with the RDC code have Recessed Dual Connector (or Recessed Dual Contact) lamp ends are typically found in F73 and more rarely F72 and F74 sizes. The RDC connector is actually a plastic piece that fits over the two bi-pins and allows the lamps to be installed in telescopic lamp ends. These are less common as the lamp end parts are significantly more expensive for the tanning bed manufacturer to use.

Like all fluorescent lamps, low pressure tanning lamps have a ballast to start the lamps and limit the flow of current. The plasma of excited mercury atoms inside the lamp emits ultraviolet light directly. The lamps are coated on the inside with special phosphors. Unlike high pressure lamps, the glass that is used in low pressure lamps filters out all UVC. Once the plasma is fully formed, the plasma literally strips away the outer electrons from the mercury; when these electrons return to a lower energy level, visible and ultraviolet light is emitted. Some of the short-wave ultraviolet excites the phosphors, which then emits photons in the proper spectrum for tanning.

History

The first tanning lamps were discovered by accident in 1903 by a German company called Heraeus who were developing lighting systems for the home and for industrial usage. These lamps were of the high-pressure metal halide variety. They discovered that the lamp that was developed for visible light purposes also emitted ultra-violet light. In the 1920s and 1930s they first started to market and sell single lamp, self standing tanning/wellness devices. The first high-pressure tanning beds incorporating more than a single high-pressure lamp were manufactured in the mid to late seventies by companies such as Ultrabronz and JK Ergoline and in the 1980s the first high-pressure units were exported to the United States.

Ballasts

Ballast used in most tanning beds. Requires a lamp starter (below) and large capacitors.

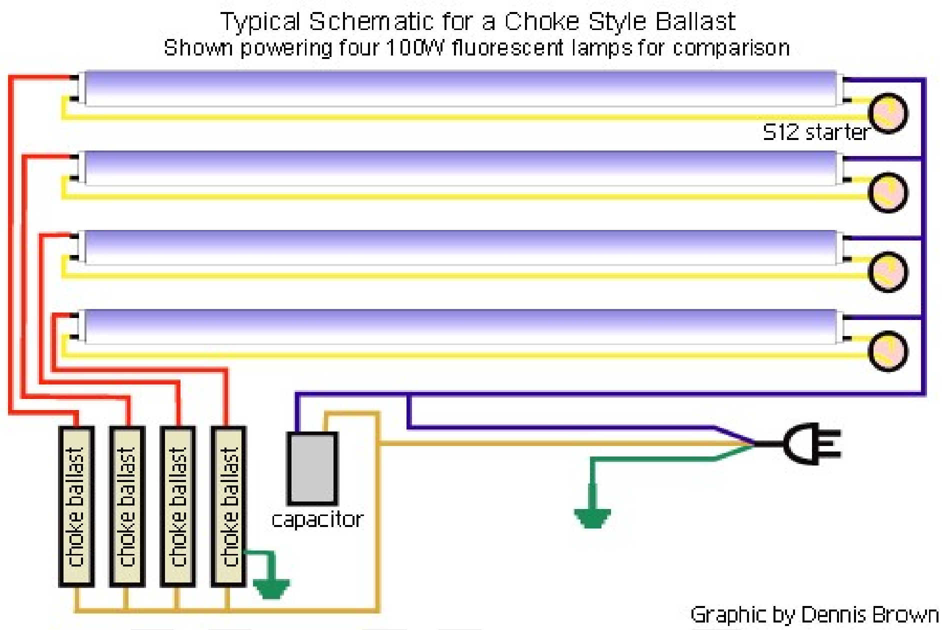
In the older style (but still most popular) "choke ballast", each end of the lamp has its own cathode and anode, however, once the lamp has started, the plasma flows from one end of the lamp to the other, with each end acting as a single cathode or anode. The starter is a plasma switch itself, and temporarily connects the cathode on one end of the lamp to the anode on the other end of the lamp, causing the lamp ends to heat up quickly, or "preheat". Many F71 lamps are still called "pre-heat bi-pin" for this reason.

Newer electronic systems work differently and always treat one end of the lamp as a cathode and one end as an anode. Whereas the choke style always works at 230 V AC at 60 Hz (220-240 V AC/50 Hz in Europe), newer electronics work very differently. This includes magnetic, pure solid state, and high frequency ballasts. These new ballasts operate at voltages up to 600 V AC, and at 20,000 Hz, with some high frequency ballasts operating as high as 100,000 Hz or higher. This allows the ballast to energize the lamp with more than raw power, and instead operates using a combination of electrical force and induction. This allows a 100 watt lamp to fully light with as little as 65 watts.

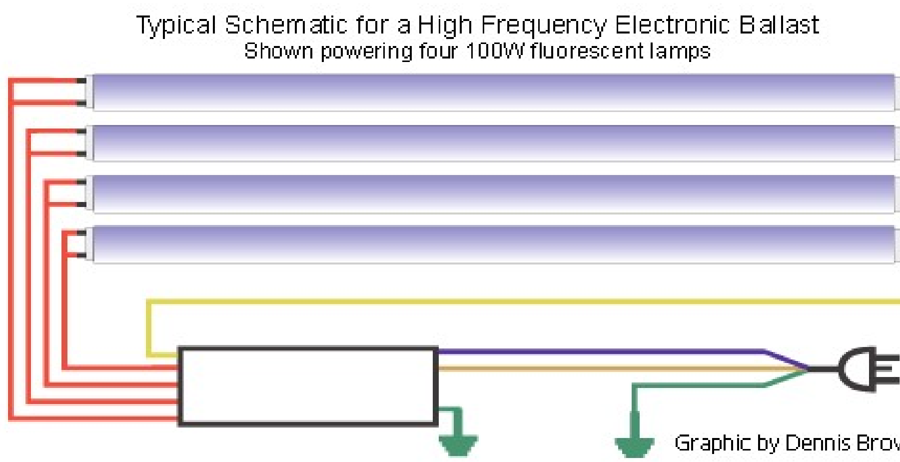
S12 lamp starter.

The advantage of the newer electronics is that they use less electricity, cost less to operate, and operate at temperatures that are well below choke ballasts. Some new electronic ballasts get as little as 10 °F (5.6 °C) hotter than ambient temperature, even after running for an extended period.

The disadvantage of the newer electronics is price. It can cost 3 to 5 times more per lamp to use electronic ballasts than traditional choke ballasts, which is why choke ballasts are still used in the majority of new tanning systems. Another disadvantage of the older style choke ballast is they are designed for European electricity, and require incoming voltage in the range of 220 V AC and 230 V AC. Most US homes have 240 V service and businesses use 208 V three-phase service that requires these beds to use a buck-boost transformer in order to receive the proper voltage. Too low a voltage will result in the lamp starter not letting the lamp ignite (or at the least, very slowly) whereas too high a voltage can lead to premature failure in the starters and lamps. The average cost of these transformers is $200 to $250. While this makes the newer electronics cost about the same for the typical tanning bed, buckboost transformers are usually sold separately, so the total cost is not always obvious to the consumer at first glance.



Schematic for Choke Ballasts: Note the use of one ballast per lamp, one lamp starter per lamp and a capacitor. Tanning beds may use 1 or several capacitors, depending on rating. These systems require 230 V AC



Schematic for HF Ballasts: It is much simpler as everything is self-contained. The main disadvantage is price, costing several times more than a choke ballast. They can be configured to run on 120 V or 230 V.

Low pressure lamp sizes and powers

Tanning lamps come in several configurations which are considered standards within the industry,including:

- **F59 and F60 -** 80 watt lamps (shorter lamps to go in front of face tanning "buckets")
- **F71, F72, F73, F74 -** Typically 100 W, although some F74 are 120 W.
- **F71 -** 160 W versions of the F71 for use in more expensive salon equipment, but a special ballast is required.
- **F71 -** 200 W versions of the F71 for use in more expensive salon equipment, but a special ballast is required.
- **F59 -** 140 W versions, shorter versions of the above lamp
- **F79, 2M -** 200 W (2 metres) used only in very expensive tanning booths and beds.

The power listing for lamps is not absolute, as you can drive a lamp with less power than listed if you use certain solid state ballasts. You can also use a 160 W lamp with a 100 W ballast, although there are no advantages to this. Using a 100 W lamp with a 160 W ballast, however, can lead to quick failure as the cathode/anode of some 100 W lamps can not take the extra power. The lamps will operate at any frequency (50 Hz to 120,000 Hz or higher). However, the ballasts and other electrical systems on the tanning bed are sensitive to frequency.

Lamp life

Like all fluorescent lamps, the low pressure lamps will burn for a long period of time. They will, however, lose their ability to produce a reasonable amount of UV after a short while. Typical lifespans for low pressure lamps are from 300 to 1600 hours of actual use although they may actually light (and produce very little UV) for as much as 5000 hours. High pressure lamps range from 300 to 1000 hours, and should be replaced when they have reached their maximum life to prevent any possible damage to the ballast, although this is very rare. Lamp manufacturers generally rate the "life" of the lamp to be the period of time that the lamp will continue to emit at least 70% to 80% of the initial UV.

Lamp types

In addition to standard lamps, there are also lamps with reflectors built inside. This is accomplished by taking the raw glass before any phosphor is used and pouring a white, opaque, highly reflective chemical on the inside of the lamp. This is done only on a certain percentage of the lamp, such as 210 degrees or 180 degrees, so that the remaining lamp is NOT coated. After this coating has dried or has been treated to ensure it will stick to the surface of the glass (using heat, for example) the lamp is coated on the inside with the phospor blend as usual. Anywhere from 3 to 5 different chemicals are typically used in a blend, with the actual proportions and chemicals closely guarded as trade secrets.

The 100 watt version of a reflector lamp is typically called a RUVA (Reflector UVA) or less commonly HO-R (High Output - Reflector). The 160 watt version are called VHO-R (Very High Output - Reflector). Although many people use the name VHR to describe 160 W reflector lamps, it is actually a registered trademark of Cosmedico, Ltd, and can only be legally used when describing their products. There are many other variations of low pressure tanning lamps including 26 watt, 80 watt, and 200 watt to name a few.

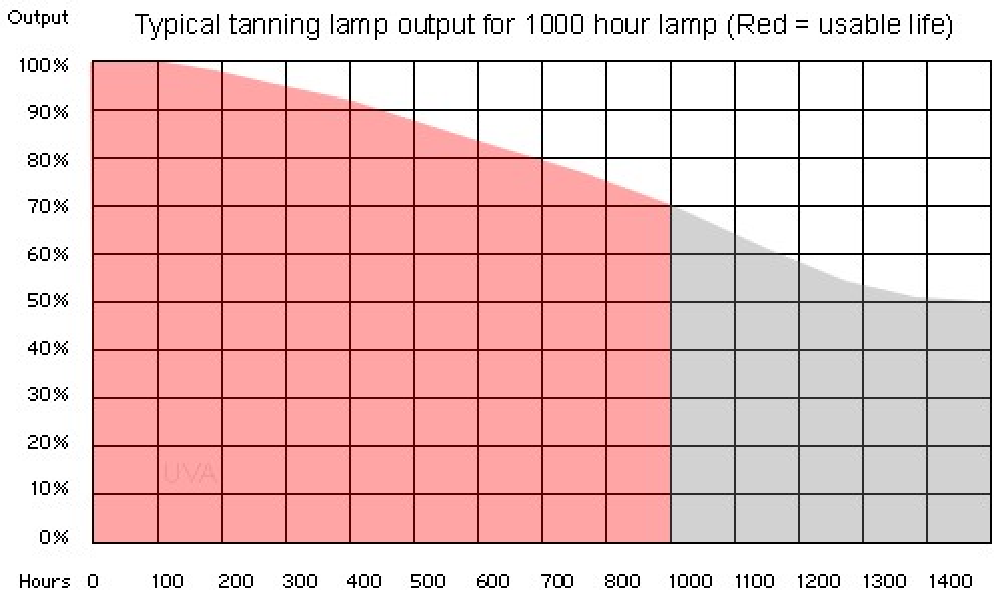
UV output rating

This is one of the most confusing aspects of tanning lamps in the US, as lamps are not rated for their total output, but rather their ratio of UVA to UVB. Most people would be led to believe that a 6.5% lamp is stronger than a 5% lamp, while both lamps might have the same total UV output (or the 5% could even be **stronger** across the spectrum). As such, the rating on lamps only tells you the relative amount of UV, making a 5% lamp really a lamp whose UV spectrum is 5% UVB and 95% UVA. There are no accepted published numbers for rating the overall power for lamps, except the TE (time exposure), which is almost as useless for making comparisons.

The TE isn't generally published, although it is usually available from the lamp manufacturer on request. Because the U.S. Food and Drug Administration (FDA) biases tests against UVB, the TE may make a weaker lamp appear stronger by having more UVB. Furthermore although tanning beds are rated with exposure times, tanning lamps are not because beds can vary widely as to how a given lamp affects the user, making it difficult or impossible to compare the total UV output of different low pressure lamps.

The UVB to UVA ratio percentage is considered an outdated form of measuring a lamp's output and Wolff now lists actual UVA, UVB and total UV flux powers. This is the best way of measuring a low pressure and high-pressure lamp. Actual Wolff lamp outputs are listed here If you are purchasing a lamp from any manufacturer always ask for actual flux power output, as UVA to UVB ratios tell very little.

Lamp maintenance and replacement



Typical output curve of a 1000 hour rated low pressure tanning lamp. At 1000 hours, the output becomes less than 70% of rated power.

Tanning lamps are virtually maintenance free, but must be kept clean as UV can easily be blocked by dust drawn in from the cooling system (or from improperly cleaned acrylics shields). Most manufacturers recommend wiping the lamps and other internals clean every 200 to 300 hours of operation. Most salons will replace their tanning lamps once per year, while home tanning bed owners can expect 3 to 5 years of use. This depends solely on the number of hours the lamps have been used and the rated life of the lamp, which varies from model to model.

High pressure lamps must be handled very carefully, as any oil from the skin that is left on the bulb can cause the bulb to overheat and lead to early failure. The filter glass must also be handled carefully as it is extremely fragile by its nature. These should only be cleaned with special chemicals designed for this purpose. Operating any tanning equipment that uses high pressure bulbs without the special filter glass is extremely dangerous, and illegal in a salon, due to the high amount of UVC generated in the bulbs.

The amount of UV that is generated from a low pressure lamp is highly dependent on the temperature in the tanning unit. As a rule, tanning lamps produce the highest amount of ultraviolet light when this temperature is between 90 and 110 degrees Fahrenheit (32 to 43 degrees Celsius). As the temperature moves away from this range, the amount of UV produced is reduced. Cooling systems for tanning equipment are usually designed to maintain a range of temperature instead of providing maximum airflow for this reason. Higher temperatures will also reduce the expected life of the tanning lamp. This is why it is important to perform regular maintenance, including checking cooling fans and insuring that vent holes are not blocked. The owners manual for the tanning equipment is the best source for maintenance schedules and methods.

Other uses

In addition to their use in tanning beds and booths, tanning lamps (or other UV producing lamps) are used for the treatment of psoriasis, eczema, and to cure or age wood used to build violins, guitars and other musical instruments. Water purification and medical instrument sterilization are both done using UVC, which low pressure tanning lamps do not emit, and which is filtered from high pressure lamps in tanning devices.

Mercury hazards

All fluorescent lamps contain mercury, and at this time, no suitable replacement has been found. Many US states have banned disposal of lamps containing mercury, and have established regulations requiring that lamps containing mercury are identified as such. This has not caused problems for manufacturers, however, as lamps are not produced locally, and often not in the US. There have been several efforts to label all lamps that contain mercury with a universally accepted symbol, Hg. Old lamps should be handled as would be any hazardous material in your locality, and persons should take special precautions when dealing with broken lamps to avoid contact with mercury. This is particularly true for pregnant women. These laws and guidelines are not unique to tanning lamps, and apply to all fluorescent lamps, other lamps that contain mercury, as well as other products that contain mercury with the exception of pharmaceuticals. Proper disposal or recycling will prevent the small mercury content of the lamps from entering the environment.

Chapter- 6

Nixie Tube

The ten digits of a GN-4 Nixie tube

A **nixie tube** is an electronic device for displaying numerals or other information. The glass tube contains a wire-mesh anode and multiple cathodes. In most tubes, the cathodes are shaped like numerals. Applying power to one cathode surrounds it with an orange glow discharge. The tube is filled with a gas at low pressure, usually mostly neon and often a little mercury and/or argon, in a Penning mixture.

Although it resembles a vacuum tube in appearance, its operation does not depend on thermionic emission of electrons from a heated cathode. It is therefore called a cold-cathode tube (a form of gas filled tube), or a variant of neon lamp. Such tubes rarely exceed 40 °C (104 °F) even under the most severe of operating conditions in a room at ambient temperature.

The most common form of nixie tube has ten cathodes in the shapes of the numerals 0 to 9 (and occasionally a decimal point or two), but there are also types that show various letters, signs and symbols. Because the numbers and other characters are arranged one behind another, each character appears at a different depth, giving Nixie based displays a distinct appearance. A related device is the **pixie tube**, which uses a stencil mask with numeral-shaped holes instead of shaped cathodes. Some Russian nixies, e.g. the IN-14, used an upside-down digit 2 as the digit 5, presumably to save manufacturing costs as there is no obvious technical or aesthetic reason.

Each cathode can be made to glow in the characteristic neon red-orange color by applying about 170 volts DC at a few milliamperes between a cathode and the anode. The current limiting is normally implemented as an anode resistor of a few tens of thousands of ohms. Nixies exhibit negative resistance and will maintain their glow at typically 20 V to 30 V below the strike voltage. Some color variation can be observed between types, caused by differences in the materials and gas mixtures used. Longer-life tubes that were manufactured later in the nixie timeline have mercury added to reduce sputtering resulting in a blue or purple tinge to the emitted light. In some cases, these colors are filtered out by a red or orange filter coating on the glass.

Applications and lifetime

The way the digits are stacked in a nixie tube is visible in this picture.

Nixies were used as numeric displays in early digital voltmeters, multimeters, frequency counters and many other types of technical equipment. They also appeared in costly digital time displays used in research and military establishments, and in many early electronic desktop calculators, including the first: the Sumlock-Comptometer *ANITA Mk VII* of 1961 and even the first electronic telephone switchboards. Later alphanumeric versions in fourteen segment display format found use in airport arrival/departure signs and stock ticker displays. Some elevators used nixies to display floor numbers.

Pair of NL-5441 Nixie display tubes

Average longevity of nixie tubes varied from about 5,000 hours for the earliest types, to as high as 200,000 hours or more for some of the last types to be introduced. There is no formal definition as to what constitutes "end of life" for nixies, mechanical failure excepted. Some sources (Weston 1968, p. 340) suggest that 50% reduction in emitted light would not be acceptable; however cathode poisoning resulting in incomplete digit display, whilst generally not preventing the tube from being used, may also be considered unacceptable. Nixie tubes are susceptible to multiple failure modes, including

- simple breakage,
- cracks and hermetic seal leaks allowing the atmosphere to enter,
- cathode poisoning preventing part or all of one or more characters from illuminating,
- increased striking voltage causing flicker or failure to light,
- sputtering of electrode metal onto the glass envelope blocking the cathodes from view,
- internal open or short circuits which may be due to physical abuse or sputtering.

Driving nixies outside of their specified electrical parameters will accelerate their demise, especially excess current, which increases sputtering of the electrodes. A few extreme examples of sputtering have even resulted in complete disintegration of nixie tube cathodes.

As testament to their longevity, and that of the equipment which used them, in 2006 several suppliers still provide common nixie tube types as service replacement parts, new in original packaging. Equipment with nixie tube displays in excellent working condition is still plentiful, though much of it has been in frequent use for 30–40 years or more. Such items can easily be found as surplus and obtained at very little expense. In the former Soviet Union, nixies were still being manufactured in volume in the 1980s, so Russian and Eastern European nixies are still available.

One advantage of the Nixie tube is that its cathodes are typographically designed, shaped for legibility. In most types, they are not placed in numerical sequence from back to front, but arranged so that cathodes in front of the one that is lit obscure it minimally. The digit sequence is rarely given; one arrangement is 6 7 5 8 4 3 9 2 0 1 from front (6) to back (1).

History

Systron-Donner frequency counter from 1973 with Nixie-tube display

The early Nixie displays were made by a small vacuum tube manufacturer called Haydu Brothers Laboratories, and introduced in 1955 by Burroughs Corporation, who purchased Haydu and owned the name *Nixie* as a trademark. The name *Nixie* was derived by Burroughs from "NIX I", an abbreviation of "Numeric Indicator eXperimental No. 1." Similar devices that functioned in the same way were patented in the 1930s, and the first mass-produced display tubes were introduced in 1954 by National Union Co. under the brand name Inditron. However, their construction was cruder, their average lifetime was shorter, and they failed to find many applications due to their complex periphery.

Burroughs even had another Haydu tube that could operate as a digital counter and directly drive a Nixie tube for display. This was called a "Trochotron", in later form known as the "Beam-X Switch" counter tube; another name was "magnetron beam-switching tube", referring to their similarity to a cavity magnetron. Trochotrons were used in the UNIVAC 1101 computer, as well as in clocks and frequency counters.

The first trochotrons were surrounded by a hollow cylindrical magnet, with poles at the ends. The field inside the magnet had essentially-parallel lines of force, parallel to the axis of the tube. It was a thermionic vacuum tube; inside were a central cathode, ten anodes, and ten "spade" electrodes. The magnetic field and voltages applied to the electrodes made the electrons form a thick sheet (as in a cavity magnetron) that went to only one anode. Applying a pulse with specified width and voltages to the spades made the sheet advance to the next anode, where it stayed until the next advance pulse. Count direction was not reversible. A later form of trochotron called a Beam-X Switch replaced the large, heavy external cylindrical magnet with ten small internal metal-alloy rod magnets which also served as electrodes.

This tube displays symbols, such as % and °C.

Glow-transfer counting tubes, similar in essential function to the Trochotrons, had a glow discharge on one of a number of main cathodes, visible through the top of the glass envelope. Most used a neon-based gas mixture and counted in base-10, but faster types were based on argon, hydrogen, or other gases, and for timekeeping and similar applications a few base-12 types were available. Sets of "guide" cathodes (usually two sets, but some types had one or three) between the indicating cathodes moved the glow in steps to the next main cathode. Types with two or three sets of guide cathodes could count in either direction. A well-known trade name for glow-transfer counter tubes in the United Kingdom was Dekatron. Types with connections to each individual indicating cathode, which enabled presetting the tube's state to any value (in contrast to simpler types which could only be directly reset to zero or a small subset of their total number of states), were trade named *Selectron* tubes.

Some Nixie-like displays made by other firms were called by various trademarked names including *Digitron*, *Inditron* and *Numicator*. A proper generic term is "*cold cathode neon readout tube*", though the phrase "nixie tube" quickly entered the vernacular as a generic name. Hundreds of variations of this design were manufactured by many firms, from the 1950s until the 1990s.

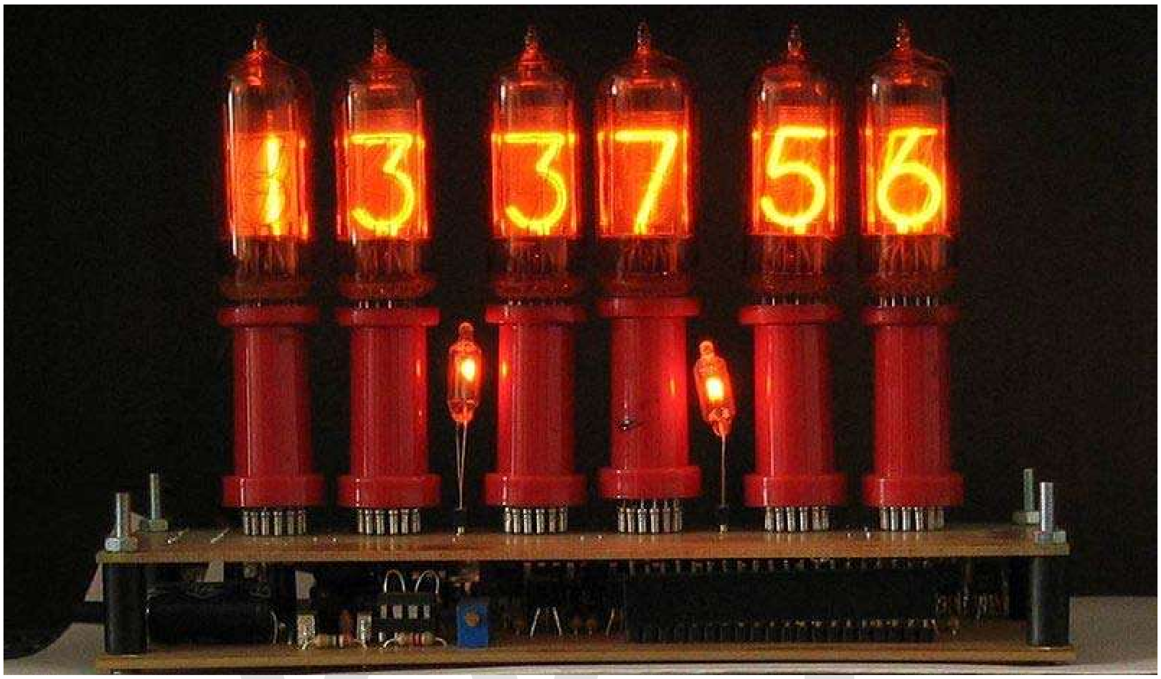
Alternatives and successors

Other numeric display technologies concurrently in use included backlit columnar transparencies, a.k.a. "thermometer displays", light pipe, rear-projection and edge-lit lightguide displays (all using individual incandescent or neon light bulbs for illumination); *Numitron* incandescent filament readouts; and vacuum fluorescent display tubes. Before nixie tubes' became prominent, most numeric displays were electromechanical, using stepping switches either directly by use of cylinders bearing printed numerals attached to their rotors, or indirectly by wiring the switches' outputs to indicator bulbs. Later, a few vintage clocks even used a form of stepping switch to drive nixie tubes.

Nixie tubes were superseded in the 1970s by light-emitting diodes (LEDs) and vacuum fluorescent displays (VFDs), often in the form of seven-segment displays. The VFD used a hot filament to emit electrons and phosphor-coated anodes, like a cathode ray tube, shaped to represent segments of a digit, pixels of a graphical display, or complete letters, symbols, or words. Whereas nixies typically require 180 volts to illuminate, VFDs only require relatively low voltages to operate making them easier and cheaper to use. VFDs have a simple internal structure, resulting in a bright, sharp and unobstructed image. Unlike nixies, the glass envelope of a VFD is evacuated rather than being filled with a specific mixture of gases at low pressure.

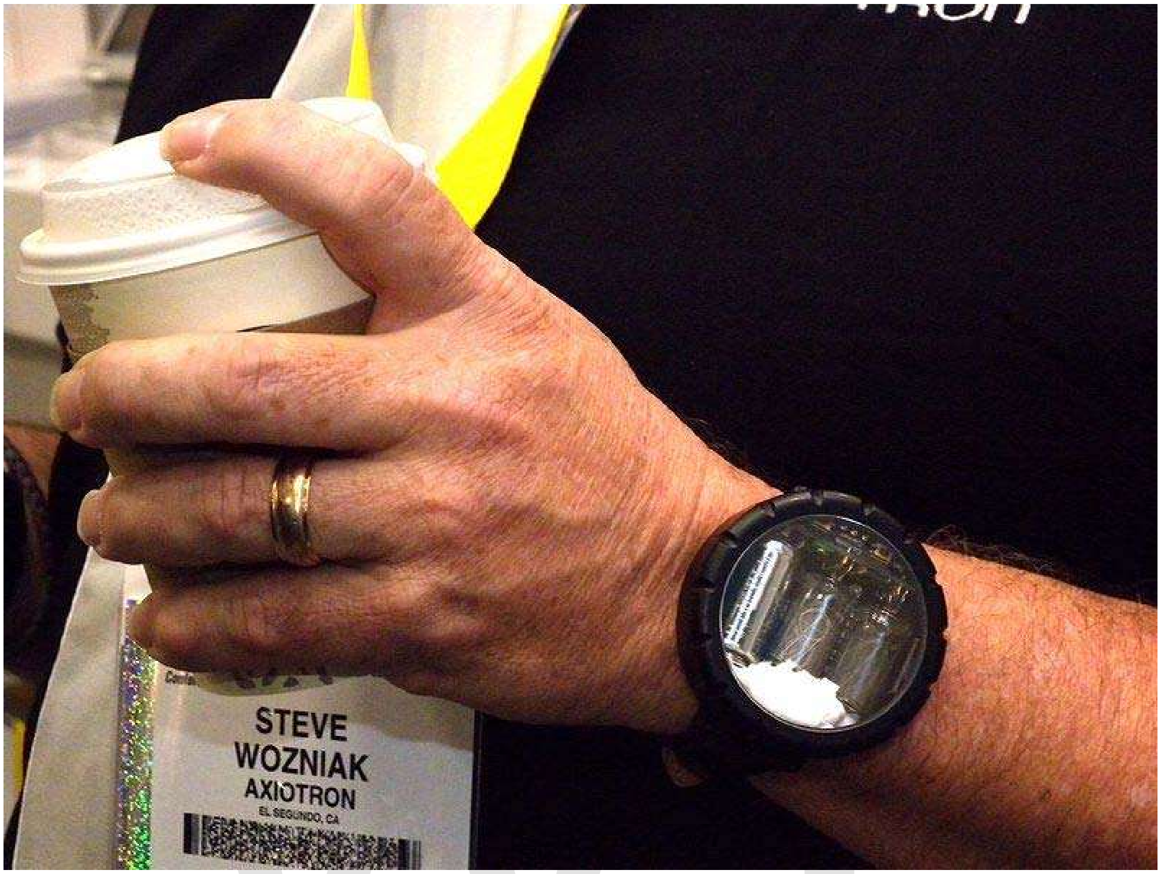
Specialized high voltage driver chips such as the 7441/74141 were available to drive nixies. LEDs were better suited to the low voltages that integrated circuits used, which was an advantage for devices such as pocket calculators, digital watches and handheld digital measurement instruments. Also, LEDs were much smaller and sturdier, without a fragile glass envelope. LEDs had lower power consumption than both VFDs and Nixie tubes.

Revival



A Nixie clock

Citing dissatisfaction with the aesthetics of modern digital displays and a nostalgic fondness for the styling of obsolete technology, significant numbers of electronics enthusiasts in recent years have shown interest in reviving nixies. Unsold tubes that have been sitting in warehouses for decades are being brought out and used, the most common application being in homemade digital clocks. This is somewhat ironic, since during their heyday, nixies were generally considered too expensive for use in mass-market consumer goods such as clocks. This recent surge in demand has caused prices to rise significantly, particularly for large tubes. The largest type known to be in the hands of collectors, the Rodan CD-47/GR-414 (220 mm [8.7 in] tall), have been sold for hundreds of dollars apiece, but these are extremely rare and only found in a few areas of the world by persistent and fortunate seekers. Prices for other large types displaying digits over 25 mm (1 in) tall have risen by double, triple or more between 1998 and 2005.



A Nixie watch on the wrist of Steve Wozniak, co-founder of Apple Inc

In addition to the nixie tube, another important consideration is the circuitry to control the tube. One of the more popular ways to do this is to use the Texas Instruments' SN74141 BCD Decoder Driver IC (or its Russian equivalents, the K155ID1 and KM155ID1, with plastic and ceramic packages, respectively). These have long since been out of production, much like the nixie tubes they were designed for.