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Lighting Intro

This is our introduction to lighting technology.

Basic Principles of Electric Lighting

In general, all electric lighting relies on the transition of electrons from a high energy state to a lower energy state. When the electron drops from one state to another, the difference in energy is emitted as light.

The actual difference between the many different kinds of electric lighting is the method that is used to excite the electrons to the higher energy level in the first place.

Incandescence

The simplest form of electric lighting is the incandescent light. The electricity is used to heat up a tungsten filament until it gets so hot it glows, emitting what is known as "black body radiation".

The term comes from the theoretical behavior of an "ideal" material. When held at the temperature of absolute zero (0°K), the material emits no radiation. Since it is completely dark, it is known as a "black body". When the material is heated, it starts to glow with emitted "black body radiation". It turns out that a hot tungsten filament behaves very much like such an ideal material.

The color of the light emitted corresponds to the temperature of the heated body. In fact, the color of a light is sometimes specified by its "color temperature", in degrees Kelvin. The common expression "red hot" comes from a simple, every-day observation of black body radiation.

One important benefit of light production via black body radiation is that the light is composed of a continuous spectrum of colors. This gives good color rendition when the light is used to illuminate objects.

Planck's Constant can be used to calculate the wavelength of a photon with a given amount of energy. The Planck law for blackbody radiation gives the intensity radiated by a blackbody as a function of frequency (or wavelength). The Stefan-Boltzmann law gives the total flux integrated over all frequencies (or wavelengths).

For details, please see:

- Planck's Constant - http://scienceworld.wolfram.com/physics/PlancksConstant.html
- The Planck law - http://scienceworld.wolfram.com/physics/PlanckLaw.html
- The Stefan-Boltzmann law - http://scienceworld.wolfram.com/physics/Stefan-BoltzmannLaw.html

Arc

A slightly more complex form of electric lighting excites electrons by passing an electric arc through a gas. The gas forms a luminous plasma, as the arc kicks the electrons up to a higher energy level and they fall back down. This is known as "arc" or "gas discharge" lighting.

The light emitted by this form of excitation generally is composed of discrete spectral lines. This gives poor color rendition when the light is used to illuminate objects. The situation can be improved by generating the arc under high pressure gasses, which tends to blur the lines, making more of a continuous spectrum of colors.

High pressure arc lights tend to use physically small bulb envelopes. Low pressure arc lights tend to use physically large envelopes.

Fluorescence

Another way to excite electrons is to hit them with light. While it might sound strange to use light to generate light, this technique is quite useful. For example, a light source might contain large amounts of ultraviolet light, which is useless for visible illumination and dangerous to the eye. But the ultraviolet can be used to excite phosphors, which then emit visible light.

Usually, fluorescence takes the form of higher energy photons (shorter wavelength) being converted to lower energy photons (longer wavelength), as is the case of invisible black light causing minerals to visibly glow.

Under certain exotic circumstances, several low-energy photons can be used to kick an electron high enough that it emits a higher-energy photon when it returns to its resting state. This phenomenon is used to produce green solid-state LASERs by shining an infrared LASER through a frequency-doubling crystal.

Fluorescence is an extremely versatile tool, since phosphors exist to generate a wide variety of colors, and they can be blended to produce shades and tints.

Efficiency Of Lighting Technology

The numerous lighting technologies differ in how efficiently they convert electricity into light.

technology	*lumens per Watt*	*efficiency*
Tungsten lamp	17	
Tungsten halogen lamp	20-25	10%
Mercury lamps	55-60	20%
Low pressure sodium lamp	more than 220	80%
High pressure sodium lamp	80-140	50%
Fluorescent lamp	65-80	40%
Compact fluorescent lamp	45-60	
Metal halide lamp	85-115	50%
HMI lamp	100-110	
Sulfur lamp	120	40%

[The lumens per Watt and efficiency numbers are collected from various sources and might not match. These figures include losses in the system, like ballast losses for fluorescents and light pipes for sulfur lamps.]

General Lighting Terminology

- bulb - Common term for the part that lights up. Professionals prefer the term "lamp".
- lamp - Technical term for the part that lights up. In common conversation, people often use "lamp" when they really mean "fixture".
- fixture - A device that holds a lamp and feeds power to it.
- luminaire - Fancy term for a lighting fixture.
- envelope - The bulbous or tubular glass part of the lamp.
- Candela - A measure of luminous intensity.
- Lumen - Metric-based unit of luminous flux.
- Candlepower - An obsolete lighting measurement.
- Footcandle - English-based unit of intensity of light falling on a surface.
- Lux - Metric-based unit of intensity of light falling on a surface.

Assorted Lamp Tips

- When installing, replacing, or tightening a lamp, do not let it directly touch your skin. Contact with skin can contaminate the lamp envelope with grease, oils, skin flakes, water, and salts.

  Organic matter on the lamp may cause hot spots when the lamp is run, even worse if the organic material carbonizes. Salts can leach into the quartz envelopes of high-tech lamps, weakening the material.

  These issues are less important with small cool lamps, but become increasingly important with lamps that run hot, like projector lamps and quartz halogen lamps. Cultivate good habits and handle *all* lamps carefully.

Measuring Light Intensity

There are several ways to measure the intensity of light.

Please note that simple intensity is not the only factor affecting *visibility*. One must also consider contrast, glare, and the color of the light (the eye is more sensitive to some colors than others).

The SI (metric system) units are:

unit name	*measure of*	*symbol*	*derivation*
Candela	luminous intensity	cd	

	luminance		cd/m^2
Lumen	flux of light	lm	cd·sr
Lux	illumination	lx	lm/m^2

Footcandle

The "Footcandle" (abbreviated "fc") is the unit of intensity of light falling on a surface, when the foot is taken as the unit of length. [As opposed to the Lux, which is used in the metric system.]

The "Footcandle" is defined as the illumination on a surface, one square foot in area, on which there is a uniformity distributed flux of one Lumen. In other words, one Footcandle is one Lumen per square foot. [It can also be defined as the illuminance on a surface that is everywhere 1 foot from a point source of one Candela.]

To convert from Lux to Footcandle:

fc = lux x .0929

Sunlight on a summer day may be higher than 10,000 fc. Moonlight might go as high as .002 fc.

Lux

The "Lux" is the unit of intensity of light falling on a surface, when the metric system is taken as the unit of length. [As opposed to the Footcandle, which is used in the English measurement system.]

It is defined as the illumination produced on a surface, one square meter in area, at a distance of one meter from a uniform point source of one Candela. In other words, one Lux is one Lumen per square meter.

The Lux is the international standard unit of illumination, and should be preferred to the Footcandle.

To convert from Footcandle to Lux:

lux = fc x 10.76

Sunlight on a summer day may be higher than 100,000 lux. Moonlight might go as high as 0.2 lux.

Lumen

The "Lumen" (abbreviated "lm") is a measure of luminous flux in the metric system. It is defined as the amount of light given out through a solid angle of one steradian by a source of one Candela intensity radiating equally in all directions.

Candela

The "Candela" (abbreviated "cd") is the modern metric unit of luminous intensity, adopted in 1948. One candela is equal to 1/60 of the luminous intensity per square centimeter of a blackbody radiating at the melting point of platinum (2046°Kelvin).

Candlepower

"Candlepower" is an obsolete lighting measurement, defined in 1860. It was defined as the light emitted by a standardized candle - made from a particular kind of material, of a particular weight, burning at a particular rate.

Sometimes "Candlepower" and Candela are used interchangeably. This is imprecise and can lead to confusion. Don't do it.

A Brief History Of Lighting Technology

If you think that the electric light was invented by Edison, you need a history lesson.

Here is a brief history of artificial lighting through the ages.

- ~400,000 BCE - Fire is discovered.
- ~13,000 BCE - Lamps are made by putting fiber wicks in natural depressions in rocks and shells, fuelled by animal fat.
- ~5000 BCE - Nut and vegetable oils come into use as fuel.
- ~3000 BCE - Oil lamps are open bowls with a spout to hold the wick.
- ~2600 BCE - Oil lamps are carved from stone.
- ~600 BCE - Oil lamps are made from pottery.
- ~500 BCE - Oil lamps become fully enclosed, with just the wick protruding, instead of open bowls.
- ~400 - The candle is invented.
- ~1550 - Georgius Agricola writes about the color of flames when mineral salts are dropped into them.
- 1667 - Robert Boyle studies bioluminescence, showing that oxygen is necessary for luminous bacteria and fungi to light up.
- 1669 - Hennig Brandt discovers phosphorus.
- 1675 - Olaf Roemer roughly calculates the speed of light to be 132,000 miles per second. When he presents his work to the French Academy of Science, he is ridiculed.
- 1678 - Christian Huygens discovers the polarization of light.

- 1725 - James Bradely calculates the speed of light to be 186,000 miles per second.
- 1752 - Thomas Melvill makes the first scientific study of the color of flames as influenced by the addition of salts.
- 1783 - Ami Argand improves the oil lamp to produce more light and less smoke.
- 1792 - William Murdock lights his home and office by burning gas made by heating coal.
- Sir Humphrey Davey invents the minor's safety lamp.
- 1800 - William Herschel discovers infrared radiation.
- 1801 - Johann Wilhelm Ritter discovers ultraviolet radiation.
- 1809 - Sir Humphrey Davey demonstrates electrical discharge lighting to the Royal Institution in London, using an open-air arc between two carbon rods. The result is a very intense, and very pure white light. Unfortunately, as the arc runs, carbon boils off and the rods wear away: constant attention must be paid to readjusting the arc, feeding more carbon in.
- 1814 - First general use of gas street lighting; London.
- 1826 - Thomas Drummond invents limelight: a piece of lime heated in an oxygen and hydrogen flame.
- 1836 - William Edwards Staite uses clockwork to keep carbon arc lamps adjusted.
- 1841 - Frederick DeMoleyns patented incandescent lamp using filaments of platinum and carbon, protected by a vacuum.
- 1849 - Armand Fizeau calculates the speed of light to be 186,300 miles per second.
- 1853 - The kerosene lamp is introduced; Germany.
- 1855 - Heinrich Geissler creates low-pressure discharge tubes that soon become a novelty sensation; Germany.
- 1857 - Serrin devises a clockwork-fed carbon arc lamp.
- 1865 - Herman Sprengel pioneers the vacuum light bulb.
- Incandescent lighting is studied by numerous scientists and inventors: Swan, Cruto, Gobel, Farmer, Maxim, Lane-Fox, Sawyer, Mann.
- 1850s and 60s - Joseph Swan demonstrates incandescent lamps with carbon filaments. Poor vacuum pump technology at the time made the lamps prone to early failure.
- 1870 - John Tyndal demonstrates the principal of "total internal reflectance" by shining light at a spout of water as it streams from a tank. The water falls in an arc and the light follows it. This is the principle behind fiber optics and light pipes.
- 1874 - Henry Woodward and Matthew Evans file the first Canadian patent for an incandescent lamp.
- 1876 - Paul Jablochkoff develops the Jablochkoff Candle, a practical arc lamp that does not require constant electrode adjustment. It has carbon electrodes side by side, with an ablative insulator that burns down at the same speed as the carbon.
- 1876 - Charles F. Brush invents a new type of simple, reliable, self-regulating arc lamp, and a new dynamo to power it. The lamp uses a solenoid and clutch mechanism to adjust the carbons.
- 1878 - The Jablochkoff Candle is used to light public places in France and Britain.
- 1878 - Thomas Edison prematurely announces successful incandescent lamp with platinum filament.
- 1879 - Joseph Swan demonstrates a carbon filament lamp. [February]
- 1879 - Thomas Edison publicly demonstrates a carbonized cardboard filament lamp, 11 months after Swan.
- 1880 - Thomas Edison receives U.S. patent #223,898 for the carbon filament incandescent lamp.
- 1880 - William Wheeler patents light pipes, using hollow pipes with reflective inner surfaces.
- 1880 - Carbonized bamboo becomes a common incandescent filament material.

- 1881 - Ludwig Piette and Franz Krizik win a Gold Medal at the Paris Electrical Exhibition for their "Pilsen lamp". It is a carbon arc lamp that regulates the carbon rods using an iron core between two solenoids.
- 1885 - Welsbach introduces the gas mantle, greatly improving the light output of gas lighting.
- 1887 - Col. Rookes Evelyn Bell Crompton builds a power station at Kensington Court, one of the first practical power supply schemes. Electric lighting is freed from relying on battery power.
- 1887 - Raphael Dubois demonstrates luciferin, used in bioluminescence.
- 1888 - Squirted cellulose becomes a common incandescent filament material.
- 1889 - A patent is granted for "flame arc lamps", with cores of flame-producing salts added to the carbon rods. The salt core increases light output and can be used to color the light.
- 1893 - An engineer named Marks introduces the "enclosed arc lamp". The arc is contained in a small glass tube within the main globe of the lamp. The restricted air flow around the arc reduces carbon rod consumption to one fifth previous rates.
- 1893 - D. McFarlan Moore introduces "Moore tube" light sources. They are cold cathode tubes, containing carbon dioxide and nitrogen gas. Lifespan is short because the gases attacked the electrodes.
- 1895 - Wilhelm Roentgen discovers X-Rays.
- 1898 - Pierre and Marie Curie discover radium, a luminous radioactive element.
- 1901 - Peter Cooper Hewitt develops the first practical mercury-vapor lamp. It uses mercury vapor inside a glass bulb with an arc lamp. The visible light is distinctly bluish green.
- Electrical discharge through mercury vapour is an excellent light source. But at low pressure most of the light is in the ultraviolet - useless and dangerous. This is the first High Intensity Discharge (HID) lamp.
- 1905 - Welsbach develops the first metal filament incandescent lamp, using osmium.
- 1908 - Tantalum is used for metal incandescent lamp filaments.
- 1907 - Tungsten is used for metal incandescent lamp filaments. Such filaments are extremely fragile.
- 1910 - "neon" sign lamps introduced by Georges Claude; France.
- 1911 - William D. Coolidge develops ductile tungsten incandescent lamp filaments. Filaments are not as fragile, and lamp life goes up.
- 1913 - Irving Langmuir pioneers the first gas-filled electric lamp, at atmospheric pressure. He also discovers that coiling the filament improves light output.
- 1915 - The first patent is issued for a neon sign.
- 1925 - Blue "neon" tubes are used, containing argon and mercury; London.
- 1926 - Harold Eugene Edgerton develops the high speed gas discharge lamp (stroboscope). [Also given as 1931.]
- 1930 - Johannes Ostermeir patents the photographic flashbulb; Germany.
- 1932 - Low pressure sodium lamps are first used commercially. Low pressure sodium lamps emit a deep orange-yellow light. They were the first really efficient lamp.
- 1933 - Various "neon" tubes are used for decoration.
- High-pressure sodium lamps improve the color, while maintaining energy efficiency.
- 1934 - The high-pressure mercury lamp is introduced. It gives a bluish white light.
- 1937 - First public exhibition of the fluorescent lamp. It uses a hot-cathode low-pressure mercury lamp, with fluorescent phosphors lining the inside of the glass. These phosphors soak up the ultraviolet light and turn it into safe, usable visible light.
- 1937 - Dick Thayer experiments with sealed-beam lamps made from "Pyrex" custard cups purchased from a hardware store. In its final form, the filament, reflector and lens are optically

aligned at the factory, and sealed into a single lamp unit. It would be known as the Parabolic Aluminized Reflector (PAR) lamp.

- 1938 - First commercial sale of the fluorescent lamp.
- 1939 - Daniel K. Wright patents an early sealed-beam lamp.
- 1940 - The first sealed beam automotive headlamps are used in cars.
- 1947 - Aldington studies electric discharge arcs in xenon gas under high pressure.
- 1955 - Kapany invents modern fiber optics.
- 1955 - Dichroic flood lamps provide a "cool" light by using a special reflector to project visible light forward while some infrared energy is dissipated out through the back of the reflector.
- 1957 - Gordon Gould invents the LASER, but is suppressed by the Defense Department.
- 1957 - The quartz halogen lamp (A.K.A. tungsten halogen lamp) is invented. In conventional tungsten lamps, the filament metal slowly evaporates and condenses on the glass envelope, leaving a black stain. In this case, the halogen removes the deposited tungsten and puts it back on the filament. This extends filament life and keeps the glass envelope from darkening. In order for this to work, halogen lamps must run hot: The envelope must be no cooler than 482°F, and sometimes has spots as high as 1250°F. In order to withstand this high temperature, the "glass" envelope is made from durable materials like synthetic quartz.
- 1960 - Theodore Maiman perfects the LASER.
- 1960 - Metal halide lamps are developed. These are essentially mercury high pressure discharge lamps with additional metal halides in their arc tubes. They produce a natural white light.
- Charles H. Townes and Arthur Schawlow are the first to actually apply for a patent on the LASER and they are the first to publish their findings in scientific journals.
- 1965 - First light emitting diode (LED).
- 1966 - Commercial introduction of the high pressure sodium lamp. It is more economical than mercury, fluorescent, or incandescent. It has a more natural color than low pressure sodium.
- 1968 - The speed of light is officially established as 186,282.3976 miles per second.
- 1968 - He-Ne LASER (red beam) is in commercial use.
- 1969 - A new form of metal halide lamp, the HMI lamp (mercury medium arc iodides) is introduced. The H stands for mercury (atomic symbol "Hg"), M is for Metals and the I is for halogen components (iodide, bromide). It provides a daylight type spectrum.
- 1970 - The Corning company produces the first practical fiber optic cable.
- Early 1980s - compact fluorescent, based on new, efficient fluorescent phosphors. These phosphors combine good color rendering, very high luminous efficacy, and are usable with higher UV levels.
- 1994 - The sulfur lamp is developed. This uses a microwave energy source of 2.45 Ghz. to bombards sulfur under argon gas in a quartz envelope. The result is a brightly glowing plasma. The output is continuous throughout the visual spectrum, but low in ultraviolet and infrared.