The Great Internet Light Bulb Book, Part I

Incandescent including halogen light bulbs

History of Incandescent Bulbs

It is widely regarded that Thomas Alva Edison invented the first reasonably practical incandescent lamp, using a carbon filament in a bulb containing a vacuum. Edison's first successful test occurred in 1879.

There were earlier incandescent lamps, such as one by Heinrich Goebel made with a carbon filament in 1854. This incandescent lamp had a carbonized bamboo filament and was mentioned as lasting up to 400 hours. At least some sources regard Goebel as the inventor of the incandescent lamp.

Joseph Wilson Swan began trying to make carbon-based incandescent lamps in 1850 and made one in 1860 that was workable except for excessively short life due to poor vacuum. He made more successful inccandescent lamps after better vacuum pumps became available in the mid 1870's.

Since that time, the incandescent lamp has been improved by using tantalum and later tungsten filaments, which evaporate more slowly than carbon.
Nowadays, incandescent lamps are still made with tungsten filaments.

Basic Principles

The filament of an incandescent lamp is simply a resistor. If electrical power is applied, it is converted to heat in the filament. The filament's temperature rises until it gets rid of heat at the same rate that heat is being generated in the filament. Ideally, the filament gets rid of heat only by radiating it away, although a small amount of heat energy is also removed from the filament by thermal conduction.

The filament's temperature is very high, generally over 2000 degrees Celsius, or generally over 3600 degrees Fahrenheit. In a "standard" 75 or 100 watt 120 volt bulb, the filament temperature is roughly 2550 degrees Celsius, or roughly 4600 degrees Fahrenheit. At high temperatures like this, the thermal radiation from the filament includes a significant amount of visible light.

For more info on incandescent lamps, try these pages at Bulbs.com:

Incandescent Lamp Workings

The incandescent lamp top page at "Lightbulb University" at Bulbs.com.

Luminous Efficiency

In a 120 volt, 100 watt "standard" bulb with a rated light output of 1750 lumens, the efficiency is 17.5 lumens per watt. This compares poorly to an "ideal" of 242.5 lumens per watt for one idealized type of white light, or 683 lumens per watt ideally for the yellowish-green wavelength of light that the human eye is most sensitive to.
Other types of incandescent light bulbs have different efficiencies, but all generally have efficiencies near or below 35 lumens per watt. Most household incandescent bulbs have efficiencies from 8 to 21 lumens per watt. Higher efficiencies near 35 lumens per watt are only achieved with photographic and projection lamps with very high filament temperatures and short lifetimes of a few hours to around 40 hours.
The reason for this poor efficiency is the fact that tungsten filaments radiate mostly infrared radiation at any temperature that they can withstand. An ideal thermal radiator produces visible light most efficiently at temperatures around 6300 Celsius (6600 Kelvin or 11,500 degrees Fahrenheit). 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.
Of course, nothing known to any humans is solid and usable as a light bulb filament at temperatures anywhere close to this. The surface of the sun is not quite that hot.
There are other ways to efficiently radiate thermal radiation using higher temperatures and/or substances that radiate better at visible wavelengths than invisible ones. This is covered by Part II of the Great Internet Light Bulb Book, Discharge Lamps. The efficiency of an incandescent bulb can be increased by increasing the filament temperature, which makes it burn out more quickly.

Vacuum vs. gas-filled bulbs

At first, incandescent bulbs were made with a vacuum inside them. Air oxidizes the filament at high temperatures. Later, it was discovered that filling the bulb with an inert gas such as argon or an argon-nitrogen mixture slows down evaporation of the filament. Tungsten atoms evaporating from the filament can be bounced back to the filament by gas atoms. The filament can be operated at a higher temperature with a fill gas than with a vacuum. This results in more efficient radiation of visible light. So why are some bulbs still made with a vacuum? The reason is that a fill gas conducts heat away from the filament. This conducted heat is energy that cannot be radiated by the filament and is lost, or wasted. This mechanism reduces the bulb's efficiency of producing radiation. If this is not offset by the advantage of operating the filament at a higher temperature, then the bulb is more efficient with a vacuum.

One property of thermal conduction from the filament to the gas is the strange fact that the amount of heat conducted is roughly proportional to the filament's length, but does not vary much with the filament's diameter. The reason this occurs is beyond the scope of this document.
However, this means that bulbs with thin filaments and lower currents are more efficient with a vacuum, and higher current bulbs with thicker filaments are more efficient with a fill gas. The break-even point seems to be very roughly around 6-10 watts per centimeter of filament. (This can vary with filament temperature and other factors. The break-even point may be higher in larger bulbs where convection may increase heat removal from the filament by the gas.)
Sometimes, premium fill gases such as krypton or xenon are used. These gases have larger atoms that are better at bouncing evaporated tungsten atoms back to the filament. These gases also conduct heat less than argon. Of these two gases, xenon is better, but more expensive. Either of these gases will significantly improve the life of the bulb, or result in some improvement in efficiency, or both. Often, the cost of these gases makes it uneconomical to use them.

How light bulbs burn out

Due to the high temperature that a tungsten filament is operated at, some of the tungsten evaporates during use. Furthermore, since no light bulb is perfect, the filament does not evaporate evenly. Some spots will suffer greater evaporation and become thinner than the rest of the filament.
These thin spots cause problems. Their electrical resistance is greater than that of average parts of the filament. Since the current is equal in all parts of the filament, more heat is generated where the filament is thinner. The thin parts also have less surface area to radiate heat away with. This "double whammy" causes the thin spots to have a higher temperature. Now that the thin spots are hotter, they evaporate more quickly.
It becomes apparant that as soon as a part of the filament becomes significantly thinner than the rest of it, this situation compounds itself at increasing speed until a thin part of the filament either melts or becomes weak and breaks.

Why bulbs often burn out when you turn them on

Many people wonder what goes on when you turn on a light. It is often annoying that a weak, aging light bulb will not burn out until the next time you turn it on.
The answer here is with those thin spots in the filament. Since they have less mass than the less-evaporated parts of the filament, they heat up more quickly. Part of the problem is the fact that tungsten, like most metals, has less resistance when it is cool and more resistance when it is hot. This explains the current surge that light bulbs draw when they are first turned on. When the thin spots have reached the temperature that they would be running at, the thicker,

heavier parts of the filament have not yet reached their final temperature. This means that the filament's resistance is still a bit low and excessive current is still flowing. This causes the thinner parts of the filament to get even hotter while the rest of the filament is still warming up. This means that the thin spots, which run too hot anyway, get even hotter when the thicker parts of the filament have not yet fully warmed up. This is why weak, aging bulbs can't survive being turned on.

Why burnout is sometimes so spectacular

When the filament breaks, an arc sometimes forms. Since the current flowing through the arc is also flowing through the filament at this time, there is a voltage gradient across the two pieces of the filament. This voltage gradient often causes this arc to expand until it is across the entire filament.
Now, consider a slightly nasty characteristic of most electric arcs. If you increase the current going through an arc, it gets hotter, which makes it more conductive. Obviously, this could make things a bit unstable, since the more conductive arc would draw even more current. The arc easily becomes conductive enough that it draws a few hundred amps of current. At this point, the arc often melts the parts of the filament that the ends of the arc are on, and the arc glows with a very bright light blue flash. Most household light bulbs have a built-in fuse, consisting of a thin region in one of the internal wires. The extreme current drawn by a burnout arc often blows this built-in fuse. If not for this fuse, people would frequently suffer blown fuses or tripped circuit breakers from light bulbs burning out.
Although the light bulb's internal fuse will generally protect household fuses and circuit breakers, it may fail to protect the more delicate electronics often found in light dimmers and electronic switching devices from the current surges drawn by "burnout arcs".

How bad a current surge bulbs draw when turned on

It is fairly well known that a cold light bulb filament has less resistance than a hot one. Therefore, a light bulb draws excessive current until the filament warms up.
Since the filament can draw more than ten times as much current as usual when it is cold, some people are concerned about excessive energy consumption from turning on light bulbs. The degree of this phenomenon has become a matter of urban folklore. However, the filament warms up very rapidly. The amount of energy consumed to warm up a cold filament is less than it would consume in one second of normal operation.

Making bulbs last longer

Long-life bulbs

Many light bulbs are made to operate with a slightly lower filament temperature than usual. This makes the bulbs last much longer with a slight reduction of efficiency.

Reduced Power

Reducing the voltage applied to a light bulb will reduce the filament temperature, resulting in a dramatic increase in life expectancy.
One device sold to do this is an ordinary silicon diode built into a cap that is made to stick to

the base of a light bulb. A diode lets current through in only one direction, causing the bulb to get power only 50 percent of the time if it is operated on AC. This effectively reduces the applied voltage by about 30 percent. (Reducing the voltage to its original value times the square root of .5 results in the same power consumption as applying full voltage half the time.) The life expectancy is increased very dramatically. However, the power consumption is reduced by about 40 percent (not 50 since the cooler filament has less resistance) and light output is reduced by reduced by about 70 percent (cooler filaments are less efficient at radiating visible light).

Soft-start devices

Since bulbs usually burn out during the current surge that occurs when they are turned on, one would expect that eliminating the surge would save light bulbs.

In fact, such devices are available. Like the diode-based ones, they are available in a form that is built into caps that one could stick onto the tip of the base of a light bulb. These devices are "negative temperature coefficient thermistors", which are resistors having a resistance that decrease when they heat up.

When the bulb is first started, the thermistor is cool and has a moderately high resistance that limits current flowing through the bulb. The current flowing through the thermistor's resistance generates heat, and the thermistor's resistance decreases. This allows the current to increase in a fairly gradual manner, and the filament warms up in a uniform manner.

However, this extends the life of the bulbs less than one might think. If the filament has thin spots that cannot survive the current surge that occurs when the bulb is turned on, then the filament is already in very bad shape. At this time, the thin spots are significantly hotter than the thicker parts of the filament and are evaporating rather rapidly. As described earlier, this process is accelerating. If the thin spots are protected from surges, the life of the bulb would be extended by only a few percent.

Additional life extension occurs only because the thermistor keeps enough resistance to result in enough heat to keep it fairly conductive. This resistance slightly reduces power to the bulb, extending its life somewhat and making it slightly dimmer.

DC vs. AC operation

As tungsten atoms evaporate from the filament, a very small percentage of them are ionized by the small amounts of short-wave ultraviolet light being radiated by the filament, the electric field around the filament, or by free electrons that escape from the filament by thermionic emission. These tungsten ions are positively charged, and tend to leave the positive end of the filament and are attracted to the negative end of the filament. The result is that light bulbs operated on DC have this specific mechanism that would cause uneven filament evaporation. This mechanism is generally not significant, although it has been reported that light bulbs sometimes have a slight, measurable decrease in lifetime from DC operation as opposed to AC operation.

In a few cases, AC operation may shorten the life of the bulb, but this is rare. In rare cases, AC may cause the filament to vibrate enough to significantly shorten its life. In a few other rare cases involving very thin filaments, the filament temperature varies significantly throughout each AC cycle, and the peak filament temperature is significantly higher than the average filament temperature.

Ordinarily, one should expect a light bulb's life expectancy to be roughly equal for DC and AC.

Why making bulbs last longer often does not pay

You may have heard that the life expectancy of a light bulb is roughly inversely proportional to the 12th or 13th power of the applied voltage. And that power consumption is roughly proportional to voltage to the 1.4 to 1.55 power, and that light output is roughly proportional to the 3.1 to 3.4 power of applied voltage. This would make the luminous efficiency roughly proportional to applied voltage to the 1.55 to 2nd power of applied voltage.
Now, if a slight reduction in applied voltage results in a slight to moderate loss of efficiency and a major increase in lifetime, how could this cost you more?
The answer is in the fact that the electricity consumed by a typical household bulb during its life usually costs many times more than the bulb does. Bulbs are so cheap compared to the electricity consumed by them during their lifetime that it pays to make them more efficient by having the filaments run hot enough to burn out after only several hundred to about a thousand hours or so.

Here is an example with actual numbers (using U.S. dollars, in 1996):

Suppose you have 10 "standard" 100 watt 120 volt bulbs with a rated lifetime of 750 hours. Such bulbs typically cost around 75 cents in the U.S. The electricity used by all ten of these bulbs is 1 kilowatt, which would typically cost about 9 cents per hour (approximate U.S. average).
Over 750 hours, this would cost (on an average) $67.50 for the electricity plus $7.50 for 10 bulbs, or $75.

Now, suppose you use these bulbs with 110 volts instead of 120.
These bulbs would consume about 87.8 watts instead of 100. However, they would only produce 76 percent of their normal light output (and this is a slightly optimistic figure). To restore the original light output, you need 13 of these bulbs. (And this will fall very slightly short.) Using 13 bulbs that consume 87.8 watts apiece results in a power consumption of 1141 watts. Over 750 hours at 9 cents per KWH, this would cost $77. This is more than the $75 cost of running 10 bulbs at full voltage even if the bulbs never burn out at 110 volts.
At 110 volts instead of 120, the life expectancy of the bulbs may be tripled. One third of 13 times 75 cents is about $3.25, which adds to the $77 cost of electricity to result in an average total cost of $80.25 for 750 hours.
This example should explain why you often get the most light for the least money using standard bulbs rather than longer-lasting ones.

How to minimize lighting costs

Higher wattage bulbs tend to be more efficient than lower wattage ones. One reason for this is the fact that thicker filaments can be operated at a higher temperature, which is better for radiating visible light.
Another reason is that since higher wattage bulbs would lead you to use fewer bulbs, you buy fewer bulbs and the cost of bulbs becomes less important. To optimize cost effectiveness in this case of higher wattage light bulbs, the filaments are designed to run even hotter to improve energy efficiency to reduce your electricity costs.
Smaller bulbs use less electricity apiece, making the cost of the bulb more important. This is why lower wattage bulbs are often designed to last 1500 to a few thousand hours instead of 750 to 1000 hours. Designing the bulbs to last longer reduces their light output and energy

efficiency.

To minimize your cost of both electricity and bulbs, you should use as few bulbs as possible, using higher wattage bulbs. To get the same amount of light with lower wattage bulbs, you need both more electricity and more bulbs.

An even better way to reduce your lighting costs is to use fluorescent, compact fluorescent, or HID (mercury, metal halide, or sodium) lamps since these are 3 to 5 times as efficient as incandescent lamps.

Halogen Bulbs

The halogen cycle, What are halogen bulbs?

A halogen bulb is an ordinary incandescent bulb, with a few modifications. The fill gas includes traces of a halogen, often but not necessarily iodine. The purpose of this halogen is to return evaporated tungsten to the filament.
As tungsten evaporates from the filament, it usually condenses on the inner surface of the bulb. The halogen is chemically reactive, and combines with this tungsten deposit on the glass to produce tungsten halides, which evaporate fairly easily. When the tungsten halide reaches the filament, the intense heat of the filament causes the halide to break down, releasing tungsten back to the filament.
This process, known as the halogen cycle, extends the life of the filament somewhat. Problems with uneven filament evaporation and uneven deposition of tungsten onto the filament by the halogen cycle do occur, which limits the ability of the halogen cycle to prolong the life of the bulb. However, the halogen cycle keeps the inner surface of the bulb clean. This lets halogen bulbs stay close to full brightness as they age.
In order for the halogen cycle to work, the bulb surface must be very hot, generally over 250 degrees Celsius (482 degrees Fahrenheit). The halogen may not adequately vaporize or fail to adequately react with condensed tungsten if the bulb is too cool. This means that the bulb must be small and made of either quartz or a high-strength, heat-resistant grade of glass known as "hard glass".
Since the bulb is small and usually fairly strong, the bulb can be filled with gas to a higher pressure than usual. This slows down the evaporation of the filament. In addition, the small size of the bulb sometimes makes it economical to use premium fill gases such as krypton or xenon instead of the cheaper argon. The higher pressure and better fill gases can extend the life of the bulb and/or permit a higher filament temperature that results in higher efficiency. Any use of premium fill gases also results in less heat being conducted from the filament by the fill gas, meaning more energy leaves the filament by radiation, meaning a slight improvement in efficiency.

Lifetime and efficiency of halogen bulbs

A halogen bulb is often 10 to 20 percent more efficient than an ordinary incandescent bulb of similar voltage, wattage, and life expectancy. Halogen bulbs may also have two to three times as long a lifetime as ordinary bulbs, sometimes also with an improvement in efficiency of up to 10 percent. How much the lifetime and efficiency are improved depends largely on whether a premium fill gas (usually krypton, sometimes xenon) or argon is used.

Halogen Bulb Failure Modes

Halogen bulbs usually fail the same way that ordinary incandescent bulbs do, usually from melting or breakage of a thin spot in an aging filament.
Thin spots can develop in the filaments of halogen bulbs, since the filaments can evaporate unevenly and the halogen cycle does not redeposit evaporated tungsten in a perfect, even manner nor always in the parts of the filament that have evaporated the most.
However, there are additional failure modes.
One failure mode is filament notching or necking. Since the ends of the filament are somewhat cool where the filament is attached to the lead wires, the halogen attacks the filament at these points. The thin spots get hotter, which stops the erosion at these points. However, parts of the filament even closer to the endpoints remain cool and suffer continued erosion. This is not so bad during continuous operation, since the thin spots do not overheat. If this process continues long enough, the thin spots can become weak enough to break from the weight of the filament.
One major problem with the "necked" ends of the filament is the fact that they heat up more rapidly than the rest of the filament when the bulb is turned on. The "necks" can overheat and melt or break during the current surge that occurs when the bulb is turned on. Using a "soft-start" device prevents overheating of the "necks", improving the bulb's ability to survive "necking". Soft-start devices will not greatly extend the life of any halogen bulbs that fail due to more normal filament "thin spots" that run excessively hot.
Some halogen bulbs may usually burn out due to filament end necking, and some others may usually burn out from thin, hot spots forming in the filament due to uneven filament evaporation/recovery. Therefore, some models may have a significantly extended life from "soft-starting" and some other models may not.
It is generally not a good idea to touch halogen bulbs, especially the more compact, hotter-running quartz ones. Organic matter and salts are not good for hot quartz. Organic matter such as grease can carbonize, leaving a dark spot that absorbs radiation from the filament and becomes excessively hot. Salts and alkaline materials (such as ash) can sometimes "leach" into hot quartz, which typically weakens the quartz, since alkali and alkaline earth metal ions are slightly mobile in hot glasses and hot quartz. Contaminants may also cause hot quartz to crystalize, weakening it. Any of these mechanisms can cause the bulb to crack or even violently shatter. If a quartz halogen bulb is touched, it should be cleaned with alcohol to remove any traces of grease. Traces of salt will also be removed if the alcohol has some water in it.
Since the hotter-running quartz halogen bulbs could possibly violently shatter, they should only be operated in suitable fully enclosed fixtures.

Use of Halogen Bulbs with Dimmers

Dimming a halogen bulb, like dimming any other incandescent lamp, greatly slows down the formation of thin spots in the filament due to uneven filament evaporation. However, "necking" or "notching" of the ends of the filament remains a problem. If you dim halogen lamps, you may need "soft-start" devices in order to achieve a major increase in bulb life.
Another problem with dimming of halogen lamps is the fact that the halogen cycle works best with the bulb and filament at or near specific optimum temperatures. If the bulb is dimmed, the halogen may fail to "clean" the inner surface of the bulb. Or, tungsten halide that results may fail to return tungsten to the filament. Halogen bulbs have sometimes been known to do strange and scary things when greatly dimmed.
Halogen bulbs should work normally at voltages as low as 90 percent of what they were designed for. If the bulb is in an enclosure that conserves heat and a "soft-start" device is

used, it will probably work well at even lower voltages, such as 80 percent or possibly 70 percent of its rated voltage. However, do not expect a major life extension unless soft-starting is used. Even with soft-starting, do not expect to more than double or possibly triple the life of any halogen bulb already rated to last 2,000 hours or more. Even with soft starting, the life of these bulbs will probably not continue to improve much as voltage is reduced to less than about 90 percent of the bulb's voltage rating.

Dimmers can be used as soft-start devices to extend the life of any particular halogen bulbs that usually fail from "necking" of the ends of the filament. The bulb can be warmed up over a period of a couple of seconds to avoid overheating of the "necked" parts of the filament due to the current surge that occurs if full voltage is applied to a cold filament. Once the bulb survives starting, it is operated at full power or whatever power level optimizes the halogen cycle (usually near full power)
The dimmer may be both "soft-starting" the bulb and operating it at slightly reduced power, a combination that often improves the life of halogen bulbs. Many dimmers cause some reduction in power to the bulb even when they are set to maximum.
(A suggestion from someone who starts expensive medical lamps by turning up a dimmer and reports major success in extending the life of expensive special bulbs from doing this.)

Ultraviolet from Halogen Bulbs

There is some common concern about the ultraviolet output of halogen bulbs, since they operate at high filament temperatures and the bulbs are made of quartz instead of glass. However, the filament temperature of halogen bulbs rated to last 2,000 hours or more is only slightly greater than that of standard incandescent lamps, and the UV output is only slightly higher. Halogen fixtures typically have a glass or plastic shield to confine any possible bulb explosions, and these shields absorb the small traces of shortwave and mediumwave UV that gets through the quartz bulb.

Higher temperature photographic and projection bulbs are different. The much higher filament temperature of shorter life bulbs results in possibly significant hazardous UV. For maximum safety, use these bulbs in fixtures or equipment designed to take these bulbs, and in a manner consistent with the fixture or equipment instructions.

For those who want to take special precautions against UV, a UV blocking clear filter gel such as the GamColor no. 1510 may be a practical solution. This filter gel withstands use moderately close to halogen lamps and withstands heat to maybe 100 to 150 Celsius or so. This filter gel can be placed immediately outside the glass shield of most fixtures, although the tubular shield in many popular 300 watt torchiere lamps gets too hot for the filter gel.
The GamColor 1510 is available at some theatrical supply shops.

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