The Incandescent Light Bulb and the Mystery of the Centennial Bulb

The basic incandescent light bulb (ILB), with a hot filament and a vacuum or inert gas fill, has served society and us well in the display industry. There still is a need for ILBs for legacy products.

by **Martin Kykta**

WE OWE A LOT TO THE INCANDESCENT LIGHT BULB (ILB), which has provided advances in industry and a better society. ILBs light our factories, offices, schools, hospitals, and roads and replaced dangerous and sooty gas lamps. The discovery led to the development of modern electronic devices. The hot filament was known to emit electrons (Edison effect), which could be collected and controlled. This led to the development of vacuum tubes, radio, television, and early electronic computers. Today, ILBs are headed toward obsolescence and replacement by LED lamps because ILBs have a low efficacy and are short-lived (1,000 hours). But that is not always the case. Take, for instance, the 60-watt Shelby bulb (called the Centennial Light) that has been in continuous operation since 1901 at a firehouse in Livermore, California. It is still operational after more than one million hours. You can visit the website to verify its longevity.[1]

We should be able to understand why the Centennial Bulb is still around. The ILB is a wire that is made hot by a current flowing through it. For inspiration, watch a YouTube video from recent MIT graduates, who were asked if they could light a bulb with a 1.5 volt battery and a wire.[2] Most graduates said yes. One person wraps the wire around the metal base of the bulb and touches the bottom of the battery with the end of the wire, and the base of the bulb to the top of the battery. The bulb doesn't light up. The graduate asks if the battery is dead or if the bulb is burnt out. One person said you need two wires. The last scene shows another graduate lighting a bulb in the same manner as the first with one wire. In the spirit of Harvard-MIT rivalry, during the video, a Harvard physics professor comments on the lack of understanding of these MIT students.

What happened? The producer of the video switched the bulb from a 120 volt, 7-watt small utility bulb with high resistance (~200 ohms) to a 2.5 volt, 2.5-watt flashlight bulb with low resistance (~1 ohm) at the very end of the video. A 1.5 volt battery cannot drive enough current through the high resistance bulb to get it to glow. Let's dismiss our smugness about such trickery and ask again, what do we know about the Centennial Bulb, and why it is still operating?

To have a practical ILB, you need several elements: (1) a filament that can be coiled and get hot (anywhere from 1800 to 3600 K) without evaporating too soon, melting, or oxidizing, (2) filament support wires on a stem and electrical leads, (3) a clear bulb that can be sealed around the filament to hold an inert gas or vacuum, (4) equipment that can evacuate the air from the bulb and seal it with inert gas or vacuum, and (5) an electrical

LAMP NO.	VOLTS	AMPS	MSCP (LUMENS /STER)	AVG LIFE (HOURS)	LUMENS	POWER (WATTS)	RESISTANCE (OHMS)	EFFICACY LUMENS/ WATT	CALCULATED TEMP FROM LM/ WATT DATA (K)	FILAMENT CALCULATED RADIUS (M)	FILAMENT CALCULATED LENGTH (M)	CALCULATED RESISTANCE AT ROOM TEMP (OHM)
60 watt tungsten (short life)	120	0.500	69.0	1,000	870.00	60.00	240.0	14.00	2753	0.000021	0.4737	19.8
60 watt tungsten (long life)	120	0.500	46.0	2,500	580.00	60.00	240.0	9.67	2601	0.000022	0.5617	21.0
OL 330BP	14	0.080	0.500	1,500	6.28	1.12	175.0	5.61	2406	0.000007	0.0461	16.7
OL 382BP	14	0.080	0.300	15,000	3.77	1.12	175.0	3.37	2212	0.000008	0.0603	18.3
Shelby cent bulb (30 W new)	120	0.208	8.4		106.00	24.90	578.3	4.26	2275	0.000040	0.0850	1,022
Shelby cent bulb (60 W new)	120	0.625	16.7		210.00	75.00	192.0	3.97	2116	0.000093	0.1461	320
Shelby cent bulb (60 W old)	120	0.033	0.014		0.17	4	3600	0.045	1452	0.000024	0.1463	4,779

Table 1.

Incandescent light bulb data from various manufacturers and the Shelby Electric Company. Additional data is calculated by the author.

isolation contact or cap to connect the leads to a power source.

Let's check the history. If you are American, Thomas Edison invented the ILB. If you are British, Joseph Swan invented it first. If you go to Wikipedia, they have a citation that lists 22 previous inventors.[3] I personally believe it was the first person to pull a hot glowing piece of metal out of a fire.

If we follow Edison's path, it involved a lot of trial and error to find a long-lasting filament. Edison was the prototypical inventor who was not a scientist and lacked a formal education, but he knew some science through experimental work as an apprentice and had some scientists and engineers working for him.

Edison's first practical filaments were made of processed carbon (carbonized cotton, linen, or bamboo) that he turned into carbon fiber in a matrix that is a composite. These carbon fibers may have consisted of layered graphene graphite in a matrix. He was able to make a light bulb, but he wanted it to be brighter, and the filament had to be hotter without breaking or evaporating. Carbon has a high melting temperature (3825 K) and a low cost. But the carbon composite would evaporate at a much lower temperature than carbon would melt, so he considered other materials, such as platinum, but it was too expensive and had a low light output because of its low melting point (2041 K).

Tungsten eventually became the material of choice because it was less brittle and tolerated small amounts of oxygen better than carbon. It too had a high melting point (3695 K) and a low evaporation rate. He also was able to achieve a greater filament temperature with tungsten than with carbon. However, tungsten is extremely difficult to work with because of its hardness. William D. Coolidge invented a complicated process to form tungsten into wires with micrometer diameters. An article by Ainissa Ramirez, "Tungsten's Brilliant Hidden History,"[4] documents this process. Without this process, it would not have been possible to make the modern tungsten filament lamp.

Operating a filament at higher temperatures produces more lumens and a shorter lifetime. For example, a 60-watt ILB with a tungsten filament has a lifetime of 2,500 and 1,000 hours at filament temperatures of 2600 and 2750 K, respectively (**Table 1**). Higher temperatures mean shorter lifetimes through evaporation. The 60-watt ILB is sealed in an inert gas of argon and nitrogen at 80% of atmospheric pressure; this slows the tungsten's evaporation rate. Using xenon gas is better because of its low heat transfer. Xenon is not commonly used because it is more expensive than argon and nitrogen. However, the inert gas also causes power loss from the filament through heat conduction and convection that would otherwise have gone to heating the filament.

An ILB that contains a halogen gas fill can run with a hotter filament (more lumens) than a normal inert gas fill. The halogen cycle redeposits evaporated tungsten back on the filament; this means a longer lifetime than an ILB with inert gas fill.

Running the ILB on DC current instead of AC will reduce the lifetime by 50% due to notching (periodic thin spots in the filament) or electro-migration.[5] Alloying tungsten with rhenium counteracts the effect. Adding silicon or aluminum oxide prevents filament droop, which will lead to cracking. Small amounts of water in the bulb will also lead to shortened lifetimes. Water disassociates into hydrogen and oxygen on the filament. The oxygen attacks the tungsten forming tungsten oxide. The tungsten oxide migrates and is reduced to tungsten and water at a cooler location. The process repeats, leading to cracking. Adding zirconium as an oxygen getter during bake-out stops the process.

What is the normal operating lifetime of a tungsten filament ILB? In 1924, industrial manufacturers purposely limited the lifetime of ILBs to 1,000 hours. Osram, Philips, and General Electric formed the Phoebus cartel to limit the life expectancy. The cartel was disbanded during World War II.[6] Today, ILBs with lifetimes as short as 40 (projection bulbs) to 100,000 hours (miniature lamps) can be purchased, depending on the application.

Turning a tungsten filament instantly on and off shortens its lifespan. The resistance is low when it is first turned on because the temperature is low. There is an onrush of current that can be 10 times greater than the average current that heats and stresses the filament. As the temperature rises, the resistance rises, and the current drops. For a carbon filament, this is not a problem. The carbon filament has a negative temperature coefficient for resistivity. When it is turned on, the resistance is high and then goes low, leading to a gradual rise in current. Tungsten is a metal, and its resistance increases with rising temperatures. Carbon is a semiconductor, and its resistance decreases with rising temperatures.

The Centennial Bulb has a carbon filament in a vacuum bulb. It was made by the Shelby electric company in the late 1890s. The glass bulb appears to be a little dark with a red filament (low temperature) glowing inside. It was originally labeled a 60-watt bulb. Today, it consumes only 4 watts. The company was purchased by GE in 1913 and closed with the name being used in catalogues until 1918. The exact process of the filament manufacture has been lost. But there is still information to be found if we can determine its physical size and electrical properties.

To find out more about the performance of ILBs, let's create a simple model. Equation 1 is a mathematical model that states the electrical power in the resistor is conducted away as heat by the leads or inert gas and is also radiated away as light. To make it easier to solve, we assume that the heat conducted away by leads is small, there is no gas in the bulb, and the operational temperature is much greater than room temperature, which leads to Equation 2. We use Equations 2–4 to arrive at Equation 5. If we know the filament's operating temperature, T_o, room temperature, T_R, and current, we can calculate the radius of the filament, r. The length, L, surface area, A_s, and cross-sectional area, A_C, follow from Equations 6–8. The resistance, R, also can be calculated, where ρ is the resistivity of the material, α is the temperature coefficient, σ is the Boltzmann's constant, and ε is the emissivity.

$$(1)\quad \frac{V^2}{R} = K(T_0 - T_R) + A_S\sigma\varepsilon(T_0^4 - T_R^4)$$

$$(2)\quad P = \frac{V^2}{R} = A_S\sigma\varepsilon T_0^4 \text{ when } K = 0 \text{ and } T_0^4 \gg T_R^4$$

$$(3)\quad P = I^2R$$

$$(4)\quad R_0 = \rho_R\frac{L}{A_C}[1 + \alpha(T_0 - T_R)]$$

$$(5)\quad r = \sqrt[3]{\left(\frac{I^2\rho_R[1 + \alpha(T_0 - T_R)]}{2\pi^2\sigma\varepsilon T_0^4}\right)}$$

$$(6)\quad L = \left(\frac{P}{2\pi r\sigma\varepsilon T_0^4}\right)$$

$$(7)\quad A_S = 2\pi rL$$

$$(8)\quad A_c = \pi r^2$$

We also need to know something about light. A blackbody curve shows the radiant power versus wavelength given off a hot body. The eye can only see a portion of that light, called the visible spectrum. The power versus wavelength sensitivity curve is bell-shaped. The perceptual unit of light power associated with sight is the lumen. From the mathematical combination of the two curves, we can produce a curve that specifies the temperature of the blackbody versus the lumens/watt (visible lumens/radiant power) or efficacy. An article by Tannous[7] has an image of the full curve. Part of the curve is given **Fig. 1**.

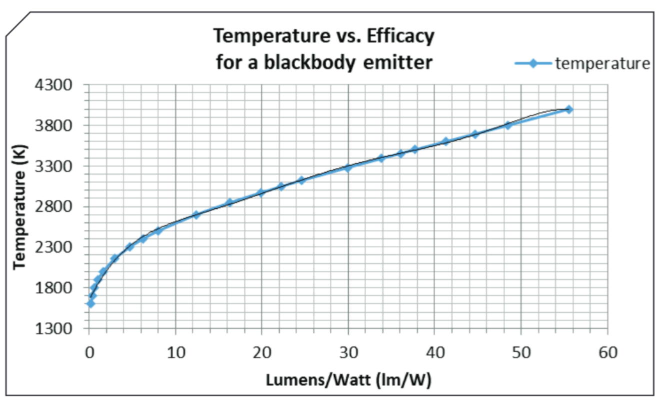

Fig. 1.

A plot of temperature versus efficacy for a blackbody emitter.

The equation for the temperature versus efficacy is

$$T = -2.736 * 10^{-6} * x^6 + 4.924 * 10^{-4} * x^5 - 3.443 * 10^{-2} * x^4 + 1.1185 * x^3 + 2.109 * 10^1 * x^2 + 2.193 * 10^2 * x + 1643 \quad (9)$$

For 1800 K < T < 3900K Where x = lumens/watt

The equation is approximate; the fit is not perfect and can be off by +/– 50 K. If you know the efficacy of the ILB, you can determine the filament temperature. The plot applies to ILBs with no gas fill.

Specific data for ILBs is in a **Table 1**. The first two rows have data on a 60-watt tungsten ILB filled with inert gas. The next two rows have data on specific miniature low-voltage ILBs with a vacuum fill. The next three rows contain data on the Shelby ILB with carbon filament in a vacuum fill. The information on the Shelby bulbs comes from several sources: a catalogue advertisement for the bulb, a study by an Annapolis student, and a study by Sandia National Laboratories. I have also added additional columns of data using simple calculations of the original data assuming either a tungsten or carbon filament.

Columns 2–7 contain the usual data provided by manufacturers. The data in columns 8–13 must be calculated. The total lumens emitted can be calculated from the mean spherical candle power (MSCP) data. MSCP is the total number of lumens emitted from the light source divided by 4π. To calculate lumens, multiply 4π*MSCP. For a tungsten filament, the resistance is smaller at room temperature. For a carbon filament, the resistance is larger at room temperature. The efficacy is calculated by dividing the total lumens emitted by the total power. The temperature of the filament is calculated from Equation 9.

What can we learn from the data in **Table 1**? Oshino, a miniature lamp manufacturer, makes the vacuum-filled ILBs listed as OL 330BP and OL 382BP.[5] Note that OL330BP has an average lifetime of 1,500 hours at T = 2405 K, and the OL 382BP has a huge increase of lifetime to 15,000 hours at T = 2211 K. A lower filament temperature means greater lifetime at the same power. There is a price to be paid; the efficacy drops from 5.61 to 3.37 lumens/watt, so less lumens are produced at the same power.

Manufacturers usually do not measure lifetimes greater than several thousand hours. They may extrapolate the lifetime data for thicker, longer filaments. The Oshino lifetime data are most likely extrapolated from closely measured experiments.

Completing the data for the Shelby lamp was difficult. The bulb is sacred to the firehouse as a good luck charm and much too fragile to be examined closely. Data were obtained by examining a substitute, unused 30-watt Shelby bulb.

In 2008, to find out more about the bulb, J. Felgar, a student, at Annapolis under the supervision of Professor D. Katz, examined a similar new 30-watt Shelby bulb. He measured the room-temperature resistance to be 1039 Ohms and the operational resistance to be 580 ohms at 120 volts and 0.208 amps. (The wattage of the lamp is closer to 25 than 30 watts). To complete the calculation of resistivity, we need to know the temperature. We can calculate the lumens from the advertisement (**Fig. 2**), which listed the candlepower (lumens = 4π* candle power) and calculated the temperature from the efficacy (see Equation 9). We then can calculate the resistivity and temperature coefficient of the carbon fiber filament from the temperature and resistance. The 30-watt bulb was then sent to Sandia National Laboratories in Livermore. They measured the radius of the filament of the 30-watt bulb to be 40 micron (see **Fig. 3a**) made of carbon. (See the Sandia report on the Centennial Bulb.[1]) The radius calculation in **Table 1** matches the experimental data.

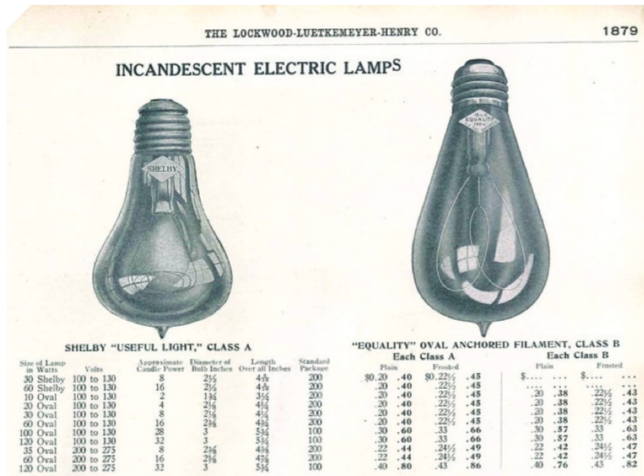

Fig. 2.

Advertisement for the Shelby lamp. Other advertisements for the Shelby lamp also listed "lamps of any voltage from 30 to 250" with "efficiencies from 3 to 4 watts [sic Lumens/Watt]" and "the longest life with the greatest economy."

For the Centennial Bulb, which was originally a 60-watt bulb, the electrical wattage is reported as 4 watts. Using this information, we can calculate the current, operational resistance, efficacy, temperature, radius, length, and room-temperature resistance of the Centennial Bulb. We can check the calculation of the length of the filament from the image of the bulb knowing the diameter (2.5 in) of the bulb from the photo of the bulb hanging in the firehouse (**Fig. 3b**). The coiled filament measurement is ~14.5 cm long, which agrees with the calculation. We can perform the same calculations for a new 60-watt Shelby bulb, which is nominally 60 watts. At 120 volts, it is 75 watts. The advertisement (**Fig. 2**) specified 60 watts in the voltage range of 100 to 130 volts. The manufacturing process was probably not that well controlled.

What did we learn about the filament material? Look at **Table 2**.

Table 2.

ILB data used to complete Table 1.

MATERIAL	RESISTIVITY (OHM-M)	TEMPERATURE COEFFICIENT α (1/K)	EMISSIVITY
Tungsten	5.60E-08	0.0045	0.30
Carbon fiber	6.00E-05	-0.00022	0.77

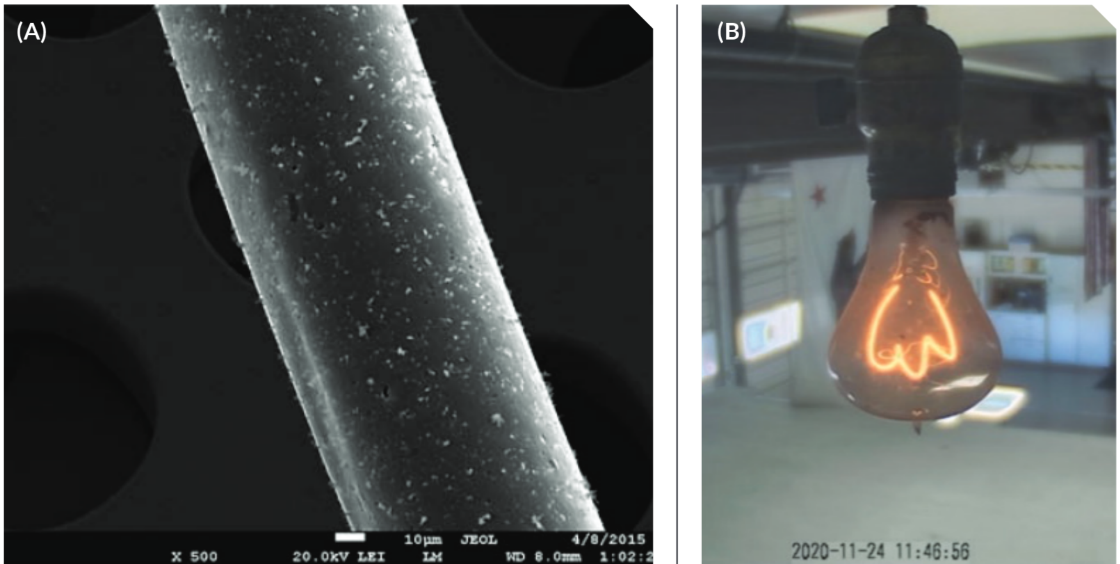

Fig. 3.

(a) A scanning electron microscope image of the carbon filament of a 30-watt Shelby light bulb taken at Sandia National Laboratories in Livermore, Ca.
(b) Photo of the 60-watt Centennial Bulb made by Shelby.

The resistivity and temperature coefficient of the tungsten filament is 5.6e-8 ohm-m and 4.5e-3 K^{-1}. The resistivity and temperature coefficient of the carbon fiber filament is 6e-5 ohm-m and −2.2e-4 K^{-1} when fit to the resistivity in Equation 4. While tungsten's resistivity is quite linear with temperature, the carbon fiber filament is nonlinear, more of a curve than a line. The results in **Table 2** for the carbon fiber filament will lead to error when calculating the resistance at either of the other two temperatures (293 K and 2175 K) that were used to make the calculation. The equation for resistivity for the carbon fiber semiconductor is an exponential function multiplied by a polynomial function (Equation 10). It can be approximated by a power function over a limited temperature range (Equation 11). This equation is necessary to achieve the resistivity calculated from the voltage versus current data to match.

(10) $\rho o = f(T) exp^{\left(\frac{E_g}{2KT}\right)}$ where $E_g = 0.033$ eV

(11) $\rho o = 2.90 * 10^{-4} * T^{(-0.274)}$

What did we learn about the lamp? The radius calculated in **Table 1** of a new 60-watt Shelby bulb is 93 microns; the 60-watt Centennial Bulb radius is now 24 microns. A lot of the carbon fiber filament has evaporated but did not break. A tungsten filament typically breaks after 25% of the mass has evaporated. They Centennial Bulb uses 4 watts of electricity; this corresponds to a filament temperature of 1452 K. The calculated light output is only 0.17 lumens. This is not a very bright lamp, but it is still operational. When the Centennial Bulb was new, the filament temperature was 2110 K and produced 210 lumens. The comparable tungsten lamp with the same temperature (~2150 K), the Oshino OL 332BP, will last 15,000 hours. The Centennial Bulb has outlasted this similar temperature tungsten lamp by at least one million hours. The reason it did not break is probably do to the strength and thickness of the carbon-fiber matrix, which led to the saying from Shelby, "the longest life with the greatest economy." Because it is operating at such a low temperature (1452 K), the Centennial Bulb may continue to last another 100 years.

The basic ILB with a hot filament and a vacuum or inert gas fill has served society and us well in the display industry. There still is a need for ILBs for legacy products. There is a need for ILBs for displays in old cars, planes, trains, electronic equipment, and specialty applications, such as inside ovens (no white LED can survive the high temperature). They will be with us for some time. Also, hot filaments are still useful for toasters, hair driers, electron microscopes, and x-ray machines. The physics of the ILB allows us to understand the lifetime, lumen, and current versus voltage performance of the ILB; they all depend on the material, radius, and length of the filament. The efficacy is large when the filament temperature is high, but the lifetime is short. The efficacy is small when the filament temperature is low, but the lifetime can be very long. In the case of the Centennial Bulb, it can last over a million hours.

References

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