The Mystery of the Centennial Bulb: an Incandescent Light Bulb©

by Martin Kykta at m.kykta@att.net

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We owe a lot to the incandescent light bulb. The incandescent light bulb (ILB) has provided for increased industry and a better society. They replaced dangerous and sooty gas lamps. ILBs lit our factories, offices, schools, hospitals and roads. 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 replacements by LED lamps because ILBs have a low efficacy and are short lived (1,000 hours). Is that really always true? How do we explain the 60 watt Shelby bulb (called the Centennial Bulb) still in continuous operation since 1901 at the fire house in Livermore California? In 2015, it was still operational after one million hours. You can visit the website that shows this bulb still in operation, Livermore's Centennial Light Bulb (centennialbulb.org) [1].

The ILB is simple right? 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 on recent MIT graduates, who were asked if they could light a bulb with a 1.5 volt battery and a wire, https://www.youtube.com/watch?v=8ve23i5K334) [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 is the bulb burnt out. One person said you need 2 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 is commenting about 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 could we know about the centennial bulb and why it is still operating?

To start with, to have practical ILB you need several elements: 1) a filament that can be coiled and get hot (anywhere from 1800 to 3600K) 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 out of the bulb and seal it with inert gas or vacuum, and 4) electrical 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 was a path of much 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 who knows some science through experimental work as an apprentice and has some scientist 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 which 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 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 much lower temperature than carbon would melt, so he considered other materials. He considered platinum but it was too expensive and a low light output due to a low melting point (2041 K).

Tungsten eventually became the 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 was also able to achieve a greater filament temperature with tungsten than 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 a filament temperature of 2600 and 2750 K respectively (see Table 1 below). 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 instead of AC current 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 manufactures purposely limited the lifetime of ILBs to 1,000 hours. Osram, Philips, 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 life. The resistance is low when its first turn 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 its turn 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 temperature. Carbon is a semiconductor and its resistance decreases with rising temperature.

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 says 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 and 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, 3 and 4, to arrive at equation 6. So if we know the filament operating temperature, T_o , and room temperature, T_R, and current, I, we can calculate the radius of the filament, r. The length, L, and the surface area, A_S , and the cross sectional area, A_C, follow from equations 7, 8, and 9. The resistance, R, can also be calculated. (Where ρ is the resistivity of the material; α is the temperature coefficient, σ is the Stefan Boltzmann constant; and ε is the emissivity. The equations for these calculations are given below:

$$\frac{V^2}{R} = K(T_o - T_R) + A_s\sigma\epsilon(T_o^4 - T_R^4) \qquad (1)$$

$$P = \frac{V^2}{R} = A_s\sigma\epsilon T_o^4 \qquad when\ K = 0\ and \quad T_o^4 \gg T_R^4 \qquad (2)$$

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

$$R_o = \rho_R \frac{L}{A_c}[1 + \alpha(T_o - T_R)] \tag{4}$$

$$r = \sqrt[3]{\left(\frac{I^2 \rho_R[1 + \alpha(T_o - T_R)]}{2\pi^2 \sigma \epsilon T_o^4}\right)} \tag{6}$$

$$L = \left(\frac{P}{2\pi r \sigma \epsilon T_o^4}\right) \tag{7}$$

$$A_S = 2\pi r L \tag{8}$$

$$A_C = \pi r^2 \tag{9}$$

We also need to know something about light. A blackbody curve shows the radiant power vs wavelength given off a hot body. The eye can only see a portion of that light called the visible spectrum. The power vs wavelength sensitivity curve is bell shaped. The perceptual unit of light power associated with seeing 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. The Article “Light Production metrics of radiation sources”, by C. Tannous [7] has an image of the full curve. Part of the curve is given below in figure 1.

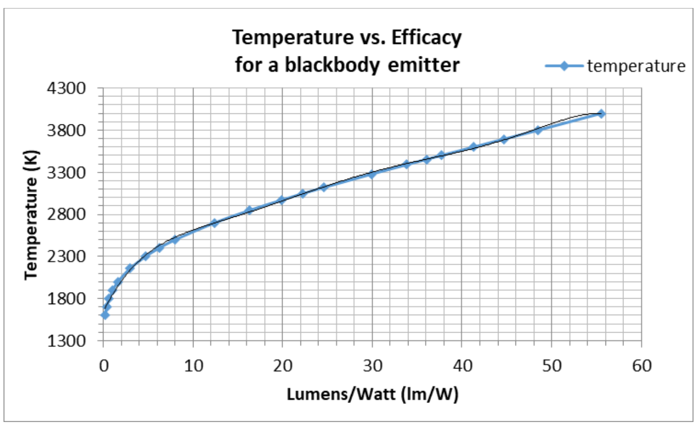


Figure 1. A plot of temperature vs. efficacy for a blackbody emitter.

The equation for the temperature vs. efficacy is given below:

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

For 1800 K<T< 3900 K Where x=lumens/watt (10).

The equation is approximate; the fit is not perfect and can be off by + or – 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 below. The first 2 rows have data on a 60 watt tungsten ILB filled with inert gas fill. The next two rows have data on specific miniature low voltage ILBs with a vacuum fill. The next 3 rows contain data on the Shelby ILB with carbon filament in a vacuum fill. The information on the Shelby bulbs come from several sources; a catalogue advertisement for the bulb, a study by Annapolis student, and a study by Sandia Lab. I have also added additional columns of data using simple calculations of the original data assuming either a tungsten or carbon filament.

Table 1. Incandescent Light bulb data from various manufacturers and the Shelby Electric company. Additional data is calculated by the author.

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	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	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 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

Columns, 2-7, is the usual data provided by manufactures. 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 get lumens just 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 10.

What can we learn from data table 1? Oshino a miniature lamp manufacturer makes the vacuum filled ILBs listed as, OL 330BP and OL 382 BP, [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; and so less lumens are produced at the same power.

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

To fill in 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 was obtained by examining a substitute unused 30 watt Shelby bulb.

Back in 2008, to find out more about the bulb, a similar new 30 watt Shelby bulb was examined by J.Felgar, a student, at Annapolis under the supervision of Prof D. Katz. 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 actually 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 (see figure 2) which listed the candlepower (lumens= 4π* candle power) and calculate the temperature from the efficacy (see equation 10). We then can calculate the resistivity and temperature coefficient of the carbon fiber filament from the temperature and the resistance. The 30 watt bulb was then sent to Sandia Lab in Livermore. They measured the filament of the 30 watt bulb radius to be 40 micron (see figure 4) made of carbon (Sandia report is on centennial bulb site [1]). The radius calculation in table 1, matches the experimental data.

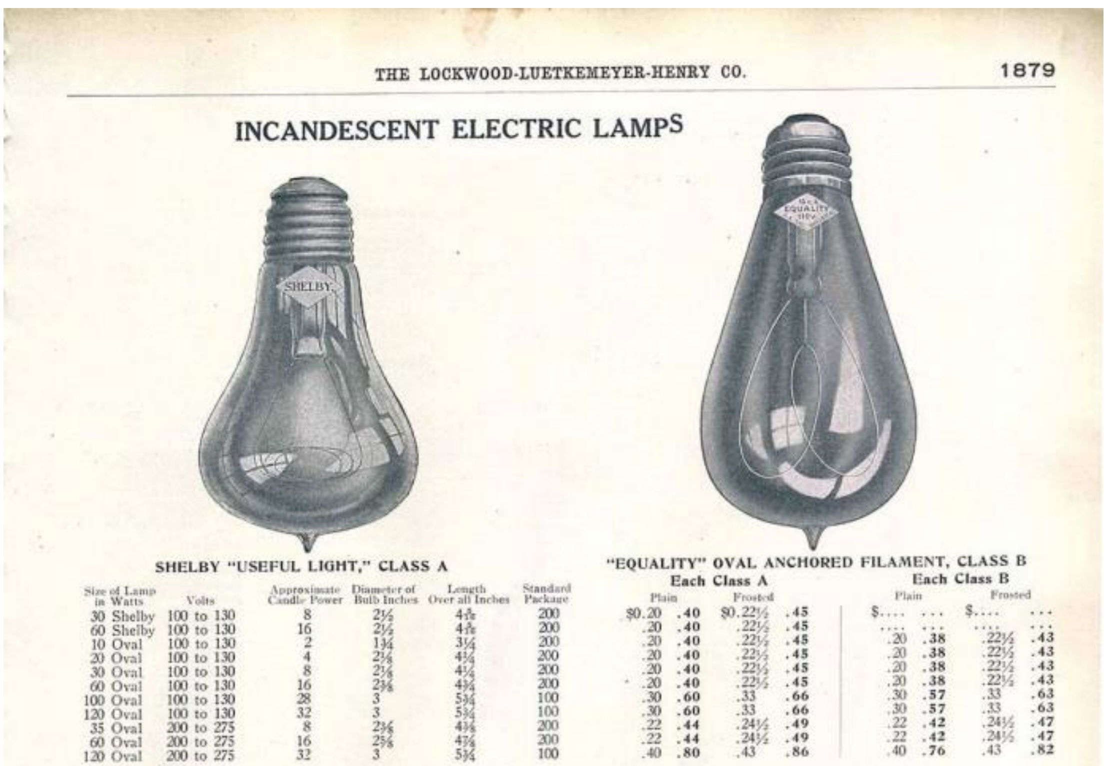
For the Centennial Bulb that was originally a 60 watt bulb, the electrical wattage is reported as 4 watts. Using this information we can calculate the current, operational resistance, efficacy, temperature, radius, length and room temperature resistance of the centennial bulb. We can check the calculation 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 (see figure 3). The coiled filament measurement is ~14.5 cm long, which agrees with the calculation. We can do the same calculations for a new 60 Watt Shelby bulb which is nominally 60 Watts. At 120 volts, it is 75 Watts. The advertisement (see figure 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. 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 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 any of the other 2 temperatures 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 (see equation 11). It can be approximated by a power function over a limited temperature range (see equation 12).

$$\rho_o = f(T)exp^{\left(\frac{E_g}{2KT}\right)} \quad where \quad E_g = 0.033\ eV \qquad (11)$$

$$\rho_o = 2.90 * 10^{-4} * T^{(-0.274)} \qquad (12)$$

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 still is 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 (~2150K), the Oshino OL332BP 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 carbon fiber matrix which lead to the saying from Shelby, “the longest life with the greatest economy". Because it is operating at such a low temperature (1452K), the centennial bulb may continue to last another 100 years.



THE LOCKWOOD-LUETKEMEYER-HENRY CO. 1879

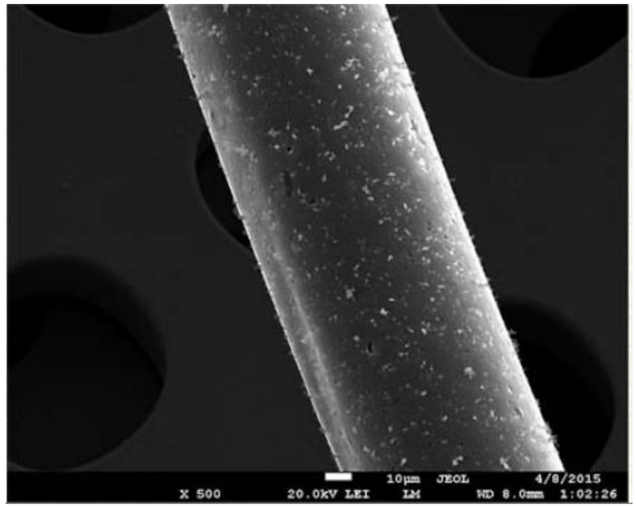
INCANDESCENT ELECTRIC LAMPS

SHELBY "USEFUL LIGHT," CLASS A

"EQUALITY" OVAL ANCHORED FILAMENT, CLASS B

Size of Lamp in Watts	Volts	Approximate Candle Power	Diameter of Bulb Inches	Length Over all Inches	Standard Package	Each Class A Plain		Each Class A Frosted		Each Class B Plain		Each Class B Frosted	
30 Shelby	100 to 130	8	2½	4 3/16	200	$0.20	.40	$0.22½	.45	$....	...	$....	...
60 Shelby	100 to 130	16	2½	4 3/16	200	.20	.40	.22½	.45	....	...	....	...
10 Oval	100 to 130	2	1¾	3¼	200	.20	.40	.22½	.45	.20	.38	.22½	.43
20 Oval	100 to 130	4	2⅛	4¼	200	.20	.40	.22½	.45	.20	.38	.22½	.43
30 Oval	100 to 130	8	2⅛	4¼	200	.20	.40	.22½	.45	.20	.38	.22½	.43
60 Oval	100 to 130	16	2⅜	4¾	200	.20	.40	.22½	.45	.20	.38	.22½	.43
100 Oval	100 to 130	28	3	5¾	100	.30	.60	.33	.66	.30	.57	.33	.63
120 Oval	100 to 130	32	3	5¾	100	.30	.60	.33	.66	.30	.57	.33	.63
35 Oval	200 to 275	8	2⅜	4⅜	200	.22	.44	.24½	.49	.22	.42	.24½	.47
60 Oval	200 to 275	16	2⅝	4⅞	200	.22	.44	.24½	.49	.22	.42	.24½	.47
120 Oval	200 to 275	32	3	5¾	100	.40	.80	.43	.86	.40	.76	.43	.82

Figure 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."



Figures 3 and 4. On the left is a photo of the 60 watt centennial light bulb made by Shelby. On the right, is a SEM image of the carbon filament of a 30 watt Shelby light bulb taken by Sandia lab in Livermore, Ca.

References

[1] Centennial Bulb organization, https://www.centennialbulb.org/
[2] YouTube, “MIT geniuses with lightbulb”, https://www.youtube.com/watch?v=8ve23i5K334
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[4] Ainissa Ramirez, ”Tungsten’s Brilliant Hidden History”, American Scientist, 2020.
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[7] C. Tannous, “Light Production metrics of radiation sources”, IAEA, 2014.