Basic Physics of the Incandescent Lamp (Lightbulb)

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Until a little over a century ago, artificial lighting was based on the emission of radiation brought about by burning fossil fuels—vegetable and animal oils, waxes, and fats, with a wick to control the rate of burning. Light from coal gas and natural gas was a major development, along with the realization that the higher the temperature of the material being burned, the whiter the color and the greater the light output. But the invention of the incandescent electric lamp in the 1870s was quite unlike anything that had happened before. Modern lighting comes almost entirely from electric light sources. In the United States, about a quarter of electrical consumption is attributed to lighting, half of that in incandescent lamps. So an understanding of the basic electrical and optical characteristics of the lightbulb is an appropriate subject for study in the introductory physics class.

The first incandescent lamps consisted of a filament of carbon wire in an evacuated glass bulb, two ends of the wire being brought out through a sealed cap and then to the electric supply. A major improvement was the development of metallic filaments, particularly those made of tungsten, now used almost exclusively in lightbulbs.

Incandescent lighting is very economical and nonhazardous to manufacture, although less energy efficient than other lighting technologies.[1] The mercury vapor fluorescent tube is more efficient; however, many states are passing restrictive regulations regarding disposal of such tubes. Currently, the most efficient commercial light source (in terms of visible light output to input energy) is the high-pressure sodium arc lamp.

Incandescent Lighting Technology

Incandescence occurs when electrical resistive heating creates thermally excited atoms. Some of the thermal kinetic energy is transferred to electronic excitations within the solid. The excited states are relieved by photonic emission. When enough of the radiation emitted is in the visible spectrum so that we can see an object by its own visible light, we say it is *incandescing*. In a solid, there is a near-continuum of electron energy levels, resulting in a continuous non-discrete spectrum of radiation.

To emit visible light, a solid must be heated red hot to over 850 K. Compare this with the 6600 K average temperature of the Sun's photosphere, which defines the color mixture of sunlight and the visible spectrum for our eyes. It is currently impossible to match the color mix of sunlight with any filament because we have no substance that can be heated to this temperature and remain solid. Of all solid filament materials, tungsten has the highest known melting temperature (3680 K) and the lowest rate of evaporation (vapor pressure) of the pure metals. Carbon can withstand higher temperatures without melting, but evaporates too rapidly. Compounds and alloys (usually metal carbides and nitrides) with higher melting temperatures and lower evaporation rates exist, but these are brittle and tend to disassociate at these very high temperatures.

Tungsten's high melting point and low vaporization pressure make it the metal of choice, but the vaporization pressure limits maximum useful filament temperature to about 3000 K. It is extremely difficult to maintain an average temperature higher than about 2900 K in standard incandescent bulbs, resulting in radiation distributions like those shown in Sidebar 1. At these temperatures, only a small fraction of the radiated energy occurs in the visible wavelengths—less than 10%, with most remaining energy radiated away at infrared (IR) wavelengths. Hence, incandescent filaments are quite inefficient
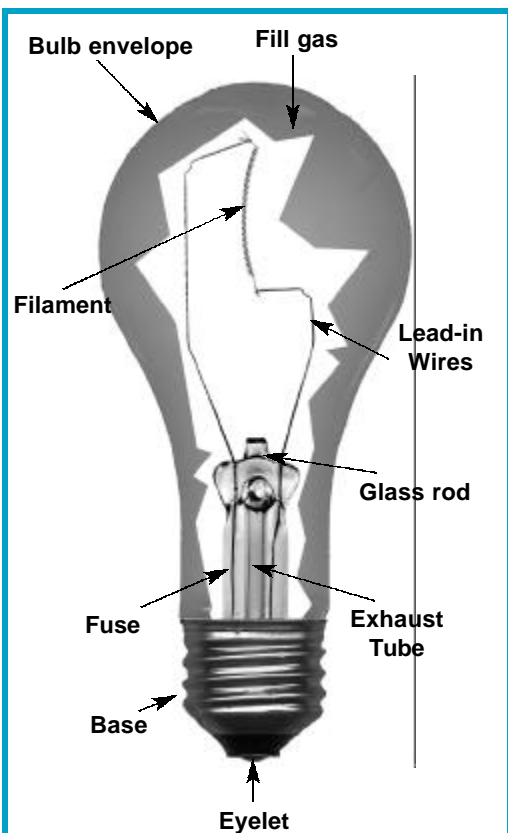
Fig. 1. Components of a standard household lightbulb of 60 W, 120 VAC.

- **Bulb envelope** is made of soft soda-lime glass; top operating temperature ~ 400 °C.

- **Fill gas**—usually argon to retard filament evaporation with some nitrogen to eliminate arcing—circulates by convection.

- **Exhaust tube** extends through bulb base and is used to evacuate, flush, and fill bulb before being sealed off.

- **Base**, made of aluminum and brass, is cemented to the bulb; cement failure is first sign of bulb's overheating.

- **Eyelet** is contact point to which electrical hot wire is soldered. Electrical return wire is soldered to threaded side portion of base.

- **Fuse** protects household circuit by melting if filament arcs.

- **Glass rod** with button that supports wires placed in it.

- **Lead-in wires** made of three welded metal sections carry current to and from filament, passing through glass seals called the stem press. Wires are designed to match expansion coefficient of the glass.

- **Coiled-coil** tungsten **filament** is designed to maintain temperature and glows yellow/orange hot at 3000 K (5000 °F). Filament is supported by mechanical clamps to lead-in and tie wires.

for visible light production, and their light is quite reddish-yellow. Low-temperature filaments (2500 to 2700 K) are particularly rich in red spectral energy and tend to bring out red in skin complexions, making people appear healthier. Higher temperature filaments (2800 to 2900 K) are relatively richer in blue wavelengths, and are paradoxically called "cooler" lights in the color sense.

While far from ideal for visible light emission, these filament temperatures are still enormous (about 3000 K, or 5000 °F), likely the hottest phenomenon we will closely encounter in our lifetimes, unless we are welding. Achieving and sustaining these temperatures requires many technical innovations (Fig. 1).

Lighting manufacturers describe the efficiency measurement or *efficacy* of incandescent lamps as the amount of visible light produced in lumens per watt (LPW) of electrical power consumed. A bar of tungsten heated to its melting point has a theoretical maximum efficacy of 52 LPW. Practical studio flood lamps achieve 33 LPW, standard 60-W household lamps with a rated lifetime of 1000 hours achieve 14.5 LPW, or 870 lumens total.

Looking at the Lightbulb

A lightbulb's glass envelope is designed to keep water vapor and oxygen away from the filament, which would otherwise oxidize the metal within seconds. Household bulbs are usually made of soda-lime glass. Silica and Pyrex™ (borosilicate) can be used for higher temperatures, to improve durability, or for ultraviolet transparency. The intricate coiled-coil mechanical design of the filament is designed to retain as much thermal energy as possible while increasing surface area and aspect ratio (Fig. 2). The lead-in molybdenum wires that support the filament and conduct current to it retain their strength at high temperatures. The National Electric Code specifies that the lead-in wire soldered to the eyelet (the bottom brass button) must incorporate a short fuse element and then be connected to the "hot" ac connection. Return is through the threaded aluminum side of the base. All modern household bulbs over 25 W are internally fused. When properly installed, it is the hot side that is fused (hence the current use of polarized plugs for lamps).

An electrostatically applied inside coat of fine silica powder called *standard coat*

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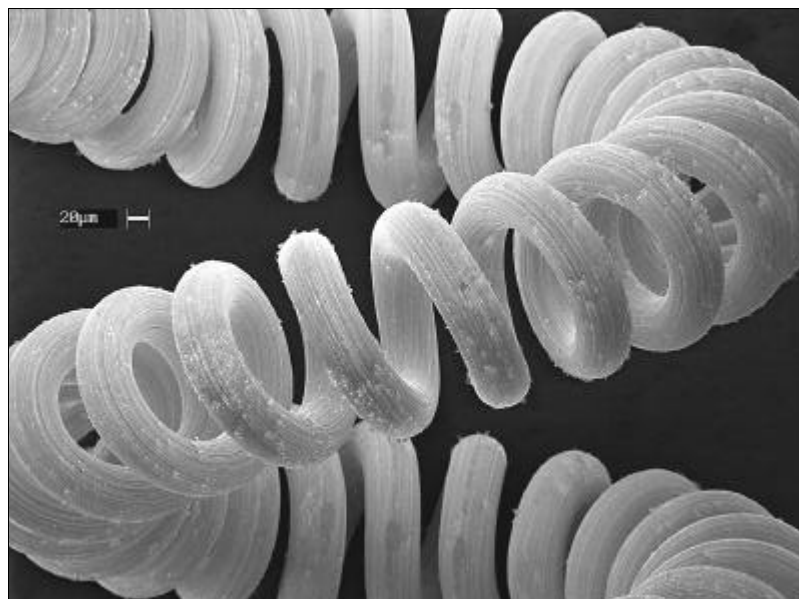
Fig. 2. Scanning electron micrograph (SEM) of a coiled-coil filament from a 60-W lamp (500X magnification). Filament winding is an incredible technical feat; readers are encouraged to break a bulb and examine the filament closely with a hand lens.

Graydon Anderson completed his Ph.D. in physical chemistry at Cornell University in 1975. For most of the time since then he has worked as an experimentalist at the Los Alamos National Laboratory on a very diverse set of projects, including laser isotope separation, sensing of high-energy particle beams, and the measurement of the physical properties of supercritical fluids. Outside of work, he enjoys the study of the physics of everyday events and common objects, and has a special interest in making physics comprehensible to nonspecialists. These pedagogical interests, as well as his long-term passion for photography, led to the present collaboration.

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spreads the brilliant filament light diffusely by Mie scattering.[2] In high-temperature bulbs, an additional reflector may be used to keep the base cool by preventing radiative warming and restricting the convection flow of the "fill gas" throughout the base.

Most modern bulbs use argon as the inert fill gas, with a small amount of nitrogen to impede arcing. Argon's high molecular weight and low thermal conductivity retards the tungsten's evaporation and insulates the filament, thereby allowing for high temperatures. The preferred krypton gas is too expensive, except for specialty lamps where long life span is a priority (traffic-signal lights, for example). Orienting the filament vertically to align it with circulating streams in the fill gas helps maintain consistent filament temperature. Pressure of the fill gas is about 80% of atmospheric pressure when cold, rising to atmospheric when in use, thereby reducing strain on the glass envelope. Lightbulbs smaller than 25 W require no fill gas, just a partial vacuum free of oxygen and water vapor.

Traditional lightbulb design is intended to maximize filament temperature, lifetime, mechanical integrity, and efficacy. Some day, filament lamp systems will exceed the theoretical maximum efficacy of melting tungsten because of new reflective bulb coatings. Such coatings (which reflect IR energy back into the bulb to further heat the filament) are currently under development, and when sufficient IR energy is reclaimed into visible wavelengths, the theoretical maximum efficacy for melting tungsten will be surpassed.

Filament Coils

The automated mass manufacturing of incandescent filaments intended for operation at over 2500 K is a significant technical achievement. Just drawing brittle tungsten into wire required the development of a special process involving doping with potassium, pressing and sintering tungsten ingots, then swaging, lubricating, and finally drawing the wire. The filament coils are made by first coiling finedrawn tungsten wire around a molybdenum wire called a mandrel, then annealing the assembly in a hydrogen-filled furnace. Annealing removes internal stresses and allows the assembly to be coiled a second time around a retractable stainless-steel mandrel and then cut to length. A second annealing is followed by an immersion in acid to dissolve the inner molybdenum mandrel.[3] The filament is then ready for mounting by mechanical clamping to two lead-in wires.

Filaments gradually degrade, and lightbulbs darken as tungsten evaporates from the filament surface to be deposited on the inner surface of the glass envelope. In the universally familiar upright bulb envelope (called the A envelope shape by manufacturers), convection currents in the fill gases will carry the tungsten atoms to the top of the envelope to accrete and blacken the bulb. Tungsten evaporates from the filament at higher temperature locations, creating a thermal runaway cycle: since filament hot spots evaporate faster, locally thinned filament locations will devel-

op higher electrical resistances that rise in temperature, thereby reinforcing localized evaporation.

At startup, tungsten filaments are so cool that the initial "inrush current" is 10 times greater than operating current, leading to strong magnetic forces between adjacent coils of the filament. This thermal and mechanical stress ensures that most degraded household bulbs will fail or "burn out" in their first second of cold startup. Expensive quartz infrared lamps counter this effect by preheating with a low voltage during startup.

The Tungsten Halide Cycle

The blackening of a bulb due to evaporated tungsten deposits can be reduced or eliminated by introducing traces of a halogen gas such as bromine or iodine. These halogens engage in a temperature-dependent cycle with tungsten vapor in which tungsten halide forms at lower temperatures (on the inside of the bulb envelope). Tungsten halide dissociates at the higher temperatures on the filament. This halide cycle will return tungsten atoms from the fill gas and the silica envelope to the filament. While bulb blackening is tremendously reduced, tungsten is unfortunately not returned to the thinnest parts of the filament—the only halogen that can do this is fluorine, which is not yet safely controllable.

Halogen lamp filaments not only *can* be run hotter and more efficiently, but *must* be run at higher temperatures to initiate and sustain the halogen cycle. Therefore, for halogen bulbs, a very small tubular envelope made of fused silica (a noncrystalline quartz) is operated at temperatures up to 1200 °C (depending on bulb type and wattage), together with a high-pressure fill gas (about five atmospheres). To ensure full lamp life, halogen filaments should be run at least 20 minutes to initiate the halogen gas cycle and fill-gas convection. Compared with non-halogen bulbs whose envelopes are made of soda-lime glass and are typically operated at 200 to 400 °C, these bulbs are much greater fire and explosion hazards.[4]

Halogen lamps are often not tolerant of changing orientations because of their strong dependence on convection gas currents. Halogen lamps are whiter and hotter (usually 3000 to 3500 K) than ordinary bulbs, and the system is more efficient (10 to 12% of the spectral energy is in visible wavelengths). Halogen lamps have become standard in automobile headlamps and projector bulbs, and for photographic use.

A Student Experiment

A simple measurement can show the dramatic effect of temperature on resistivity of tungsten. Measure the resistance of a 60-W bulb with an ohmmeter. The built-in voltage is provided by a 1½-V battery. The resistance will be about 18 Ω. Consider, however, that when the bulb is used in a 120-V circuit, its resistance must be R = (120 V)^2/60 W = 240 Ω. The current surge when the bulb is first turned on is about 7 A.

Acknowledgments

References

1. See, for instance, OSRAM Sylvania publications: Engineering Bulletin IN002 (*Incandescent Lamp Manufacture*); Engineering Bulletin IN003 (*Incandescent Lamps*); Engineering Bulletin 0-349 (*Tungsten Halogen Lamps*); and the 1996 catalogs for Light Products and Large Lamps. See also the General Electric publication *Incandescent Lamps*.

2. E. Hecht, *Optics* (Addison Wesley, 1987), p. 539.

3. A standard General Electric 60-W 120 VAC lamp filament starts as a 53.3-cm length of tungsten wire having a 46-micron (4.6 × 10^5 m) diameter. It is first wound into a coil of 1130 turns 8.3 cm in length over a molybdenum mandrel and then coiled a final time to 2 cm in length around a steel mandrel.

4. Underwriter Laboratories refuses to certify halogen torchiere (floor standing) lamps over 300 W as safe. http://gohper.fiu.edu/orgs/ehs/halogen.htm suggests that consumers replace bulbs over 300 W in such lamps. For further safety, high-wattage halogen lamps should also have glass bulb shields.

5. B. Merik in *Light and Color of Small Lamps* (General Electric publication).

6. *Handbook of Chemistry and Physics,* 75th ed. (Chemical Rubber Company, Boca Raton, 1994), p. 10-296.

Sidebar 1. Incandescent Lamp Emission Curves

To calculate the portion of light emitted at visible wavelengths, we compare the filament to a theoretical blackbody radiator. The rate P_r at which any object emits energy via electromagnetic radiation is dependent upon its area and temperature to the fourth power: $P_r = \sigma \epsilon A_{obj} T^4$, where in SI units P_r is power radiated in watts, ϵ is the emissivity ($\epsilon = 1$ for a theoretically perfect radiator (or a "blackbody"), A_{obj} is the object's surface area in m^2, and T is temperature of that area in kelvin.

At a particular wavelength λ, the radiation emitted by a perfect blackbody radiator is described by Planck's radiation law:

$$I(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{-hc/\lambda kT} - 1}$$

where T is the temperature (in K), h is Planck's constant, c is the speed of light, and k is Boltzmann's constant (1.3×10^{-23} J/K). $I(\lambda, T)$ is known as the *spectral exitance*, which is a flux of power per unit area per unit wavelength, and therefore has SI units of W/m^3. Figure 1 shows the spectrum of $I(\lambda, T)$ for perfect blackbodies at three different temperatures corresponding to the operating temperatures of tungsten bulbs operating at 60, 100, and 150 W.[1]

Only a small fraction of a bulb's intensity is emitted at visible wavelengths (390 to 780 nm), as indicated by the shaded area in Fig. 1. This fraction was determined (Table I) for three bulbs by numerically computing the area A(T) under each curve in the visible region and then dividing that area by the total radiant flux density $I(T)$ for each temperature. $I(T)$ is given by the Stefan-Boltzmann law:

$$I(T) = \int_0^\infty I(\lambda, T) d\lambda = \sigma T^4$$

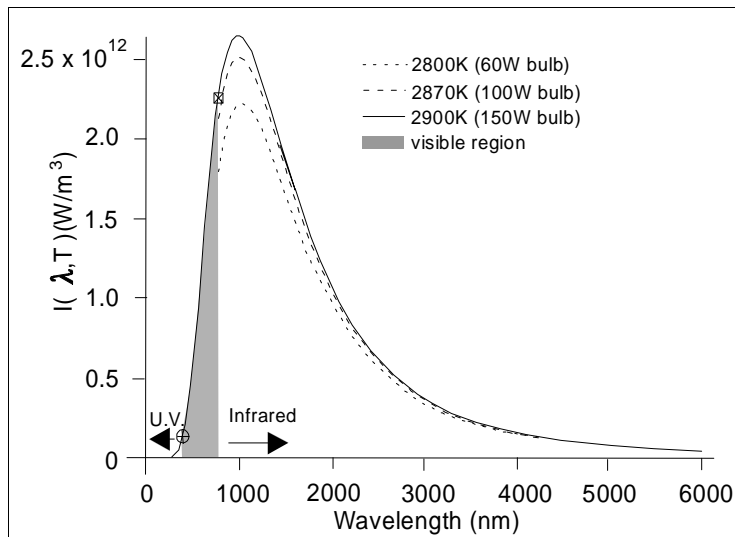where σ is the Stefan-Boltzmann constant (5.67×10^{-8}

Fig. 1. Blackbody radiation curves for three different temperatures, corresponding to lamps of different power ratings. Shaded area shows wavelength region of visible light. For clarity, the area in the visible region for a 150-W bulb is shown, which entirely overlaps respective areas of 60- and 100-W bulbs.

W/m$^2 \cdot T^4$). In this calculation we have made two idealizations: first we ignored the transmissivity of the glass envelope; its effect on visible light would be small. The portion of light emitted in the visible range is about 10%. Second, by treating tungsten as a blackbody, we have also ignored the emissivity ϵ, which is dependent on both wavelength and temperature. The emissivity of tungsten decreases the emission by a substantial amount (more than a factor of two in the visible) and shifts the maximum of $I(\lambda, T)$ slightly towards shorter wavelengths.[5] However, since the spectrum of ϵ for tungsten is approximately independent of T for lightbulb operating temperatures, the spectrum of $I(\lambda, T)$ for tungsten will behave like a blackbody of a somewhat different T. Additionally, the ratio of $A_{curve}(T)/I(T)$ is still close to 10% for real tungsten because the blue shift of $I(\lambda, T)$ due to ϵ is small.

Power (W)	Temperature (K)	Visible flux density A(T) (10^5 W/m^2)	Total radiant flux I(T) (10^6 W/m^2)	% Emission in visible A(T)/I(T)
60	2800	3.389	3.49	9.7
100	2870	4.124	3.85	10.7
150	2900	4.474	4.01	11.2

Table I. Lightbulb characteristics at visible wavelengths, as determined from Planck's radiation law and the Stefan-Boltzmann law (assumes $\epsilon = 1$).

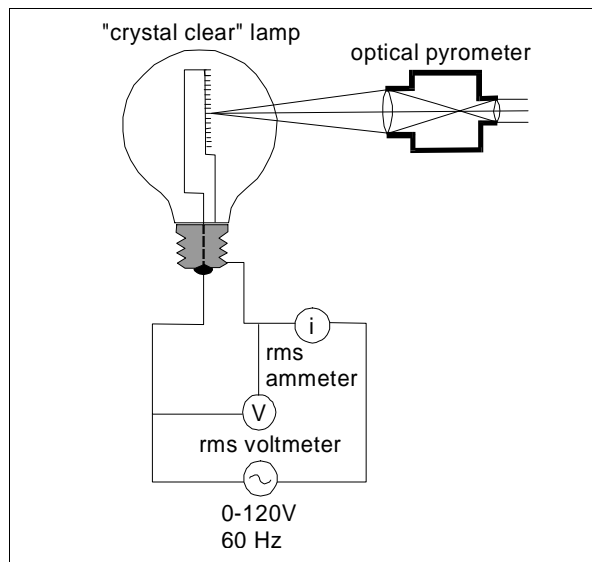# Sidebar 2. Optical and Electrical Properties of an Incandescent Lamp

We measured the current-voltage characteristics of a GE®60-W "crystal clear" incandescent lamp to show how the filament resistance increases dramatically as the filament heats up. The clear glass bulb envelope also allowed us to simultaneously measure the temperature of the filament using an optical pyrometer. Apparatus setup is shown in the figure.

Alternating current at 60 Hz was supplied to the bulb by a Variac that could adjust the voltage from 0 to 140 V. Digital multimeters (Tektronix DM501) simultaneously measured the voltage and current supplied to the filament. Filament temperature was measured using a Leeds and Northrup model 8622-C optical pyrometer.

In an optical pyrometer, the image of the object whose temperature is to be measured is superimposed on the image of a standard filament inside of the pyrometer. A red filter limits the bandwidth to the wavelength region of 0.65 microns. The operator varies the current in the standard filament until it appears to have the same brightness as the unknown object. For this reason, the measured temperature is often referred to as the *brightness* temperature. The current-adjusting dial is calibrated to directly read out the "effective blackbody temperature" of the unknown object.

Usually, the object to be measured is not a true blackbody, necessitating a correction to the temperature determination. In effect, we ask the question, "What temperature would a *graybody* (an imperfect blackbody) with emissivity ϵ require in order to be as bright at $\lambda = 0.65$ μm as a blackbody at temperature T_B?" The answer comes from the Planck distribution law. Equating the brightness of a graybody with an equivalent blackbody, we get

$$\frac{2\pi hc^2\epsilon}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1} = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT_B}-1}$$

"crystal clear" lamp
optical pyrometer
i rms ammeter
V rms voltmeter
0-120V 60 Hz

This equation can be solved to determine the true corrected value of T for the graybody given the brightness temperature T_B measured by the pyrometer and the value of the emissivity of the source, ϵ. A small complication in our lamp experiment: the glass envelope reduces the brightness of the filament by approximately 8%, due to 4% reflection losses at each glass surface. However, this can easily be treated as an effective reduction in the emissivity of the source.

Reference 6 gives the emissivity of tungsten at 0.65 microns and at temperatures near 2900 K as $\epsilon = 0.420$. We calculate an effective emissivity for a filament in a glass envelope using $\epsilon_{eff} = (0.92)(0.420) = 0.386$.

Knowing ϵ_{eff}, T_B, and the constants, we numerically solve the equation for the values of corrected filament temperature T as shown in Table II. The results of our measurements and the applied corrections due to the effective emissivity are given in the table. Note the large increase (14.4×) in the filament resistance between room temperature and the normal operating point of the lamp.

rms voltage (volts)	rms current (amperes)	Power (watts)	Filament resistance (ohms)	Apparent blackbody temperature T_B(kelvin)	Corrected filament temperature T (kelvin)
0	0	0	16.85	-NA-	297
70.27	0.3710	26.07	189.4	2223	2459
79.99	0.3976	31.80	201.2	2278	2526
90.00	0.4234	38.11	212.6	2373	2644
100.04	0.4479	44.81	223.3	2468	2762
109.97	0.4710	51.80	233.5	2563	2882
119.95	0.4931	59.15	243.3	2588	2913

Table II. Current-voltage-resistance-temperature characteristics of a clear 60-W incandescent lightbulb.