

Light Bulbs

Name _____ Box _____

Purpose: To study resistivity, radiant energy, and power transfer using a light bulb.

Theory: An object radiates heat to its surroundings and absorbs heat from its surroundings. The equilibrium temperature of an object depends on the relative amounts of emitted and absorbed energy. In general, a hot object radiates more energy than it receives. For a hot object to maintain a constant temperature it must be continuously re-supplied with energy to replenish the energy lost to its surroundings. The rate at which the energy needs to be replenished, the power input, must match the rate at which energy is being radiated to the surroundings, the power loss or the power output.

The power output of a radiating body depends on its temperature according to the ***Stefan-Boltzmann Law***

$$\text{Power output} = \sigma e A T^4$$

Where

σ = a universal constant known as the Stefan-Boltzmann constant
= $5.6687 \times 10^{-8} \text{ W/m}^2\text{K}^4$

e = the emissivity of the surface, with a value between 0 and 1, where 1 means an ideal (black) body; real (gray) bodies have $0 < e < 1$.

A = the surface area of the body

T = the absolute temperature of the body

An ideal black-body radiator would have an emissivity of 1.0000. A so-called gray-body, like our tungsten filament, will have an emissivity between 1 and zero.

In addition to the Stefan-Boltzmann Law, resistive bodies, like our light bulb filament, also obey the resistivity equation

$$R = \rho(L/A_x)$$

Where

R = the resistance

ρ = the resistivity of the material

L = the length of the resistive material

A_x = the cross-sectional area of the body

(do not confuse A with A_x , they are not the same quantity)

We will measure the power by making independent measurements of both voltage, V , and current, I , through the light bulb. Then,

$$P_{in} = IV = I^2R = I^2 \rho(L/A_x) = \sigma e A T^4 = P_{out}$$

(Under most circumstances we can safely ignore the relatively small contribution to P_{in} from energy absorbed from the surroundings. At room temperature and at temperatures above about 1000K we can also safely ignore power losses due to convection by gas in the bulb and losses due to heat conduction into the other materials in the bulb. Since the power input and power output are going to be equal under these conditions, we will refer to either or both of them simply as “the power”, P .)

The resistivity of Tungsten is well studied. You have a graph of Temperature vs Resistivity for temperatures ranging from 300 K to 3655 K. From the best-fit power relation to this data we can say, for a glowing light bulb, that

$$(T / T_0) = (R / R_0)^{0.82984}$$

Where

T_0 = room temperature

R_0 = the resistance of the filament at room temperature

T = the temperature of the glowing filament

$R = V / I$ = the resistance of the glowing filament

Knowing $R = V / I$, R_0 , and T_0 we can use the power-fit exponent to solve for T , the filament temperature.

A very good estimate of the length of the filament can be obtained using an overhead projector to put a magnified image of the filament on a screen. It is a simple matter to work out the magnification factor and convert the length of the filament measured on the screen to the actual length.

Once L is known, A_x can be calculated from the resistivity equation. From A_x we can calculate the radius of the wire, r (because $A_x = \pi r^2$), and from r and L we can calculate the area of the filament using the formula for the area of the side, without the ends, of a cylinder.

$$A = 2 \pi r L$$

This is a class demonstration lab. With the assistance of the instructor, each class will gather a set of data to be shared by all class members, but each student will be responsible for completing his or her own analyses.

Procedures:

There is one basic circuit used for making all the electrical measurements. The apparatus will be set up at the beginning of the period by the instructor. Neatly sketch this circuit in the space below.

Part I: Measure the length, L , of the light bulb filament. Use a thermometer to measure room temperature. Enter these two measured quantities in the upper section of Data Table II.

Part II: The first thing we need is the resistance of the filament at room temperature. We'll measure this two ways; *i*) direct measurements using several multimeters as ohmmeters; and *ii*) using a graphical analysis of very low power V vs I readings. The resistance of our filament is temperature dependent so these measurements must be made at very low power to prevent heating the filament above room temperature. The graph itself will allow us to determine if the power is low enough to prevent heating. We know that $V = IR$, so a plot of V vs I should be a straight line (as long as the temperature is constant) with a slope of R . If the power gets too high, this line will start to curve. We will analyze the low power, straight line, section of this graph to find the resistance of the filament at room temperature. The results of all these measurements go into Data Table I.

Part III: Use the 4th-order polynomial fit to the tungsten resistivity vs temperature graph to calculate the resistivity of tungsten at room temperature, ρ_0 . Enter this value into the appropriate line of Data Table II.

Part IV: Measure the current at ten voltages from 2V to 20V. Enter the results in the body of Data Table II.

We will make three attempts to determine the surface area of the filament, A .

- i) Use $R = \rho L/A_x$; Use the room temperature measurements of R_0 and L , to find the ratio ρ_0/A_x ; Use the polynomial fit of the tungsten data in the resistivity vs temperature graph to determine ρ_0 , the

resistivity of the filament at room temperature. With that we can calculate A_x , the cross-sectional area of the tungsten filament.

Since $A_x = \pi r^2$, we can easily find the radius of the filament.

Then we can use the radius and the length to calculate the surface area of the filament, A_s , since $A_s = 2\pi rL$

ii)

Analyses:

Data Table I

The room temperature resistance of the filament, R_0 , was measured with four different multimeters. The resistances of the other metal components of the light bulb are so low that we are justified in assuming that the entire resistance of the bulb is due to the resistance of the tungsten filament. Calculate the average of those four measurements and enter it in Data Table I.

Use Graphical Analysis to construct two graphs of the lower power data in Data Table I. Plot it both ways; V vs I and I vs V . Either way the graph should be a straight line. If the line curves, you will have to select the lowest energy portion where it is still straight. One graph has a slope of R_0 and the other graph has a slope of $1/R_0$. Use a linear fit to determine both estimates of R_0 . Provide printed copies of both graphs in the usual format.

The instructor will inform each student what to use as the “correct value” of R_0 .

Data Table II

The resistance of a wire is given by $R = \rho L/A_x$, where ρ is the resistivity of the wire, L is the length of the wire, and A_x is its cross-sectional area.

1. Measure the length of the filament in the bulb: $L = \underline{\hspace{2cm}}$ m
(The resistance of the other wires in the bulb is small enough to be ignored. Use an overhead projector to magnify and measure the filament w/o breaking the bulb.)
2. Now set the multimeter to Ohm measurement and measure the resistance of the cold tungsten filament wire. Take an average of several measurements. This has to be accurately measured. Be equally careful with the thermometer. Don't touch the bulb and don't touch the thermometer any more than necessary. We want the room temperature uncontaminated by heat from your hands.

$$\begin{aligned} \text{Cold Resistance of the filament} &= R_0 = \underline{\hspace{2cm}} \Omega \\ \text{Current room temperature} &= T_0 = \underline{\hspace{1cm}} \text{ C} = \underline{\hspace{1cm}} \text{ K} \end{aligned}$$

3. Set up the circuit with the DC power supply, ammeter, voltmeter and bulb according to the diagram on the board. Complete the first three columns of both data tables (voltage: 2-20V; current; & color). The other columns will be calculated later.
4. Those who want to make it easy on themselves will duplicate data tables II & III in a two page Excel spreadsheet and use it to make all their calculations. Those who do so should provide a printout of the final tables and save a copy of the file

(Lab28-username.xls) in the “F:\physics” folder so the instructor can review your methods. Include your name in the upper-right-hand corner on the printouts and on both spreadsheet pages in the spreadsheet file.

Data Table II - Calculations

The calculations and procedures in this section apply to Data Table II, only. Begin by entering the values for L , R_0 , and T_0 measured above into the top section of Data Table II. Tungsten's properties are well documented. You have been provided with two graphs showing plots of its temperature vs resistivity and resistivity vs temperature. The first of these includes both a power fit and a fourth order polynomial fit to the data.

5. Use the information on the enclosed printout from Graphical Analysis to calculate the resistivity at the tungsten filament at room temperature.

The quickest way to do this

The resistivity of the cold bulb filament material: $\rho_0 =$ _____ $\Omega \text{ m}$

4. Now calculate the cross-sectional area of the wire: $A_x =$ _____ m^2

5. Next, calculate the radius of the wire: $r =$ _____ m

6. Now you can calculate the surface area of the tungsten filament using $A_s = 2\pi rL$.

(Enter this result in Data Table I, only)

$A_s =$ _____ m^2

Analysis:

We are using two data tables in this lab to look at the problem of radiant energy transfer from two points of view. To generate the results in Data Table II we will be using standard data along with our own to make an estimate of the emissivity of the tungsten filament and the value of the Stefan-Boltzman constant. To generate the results in Data Table III we will use the known value of the Stefan-Boltzman constant to calculate the resistivity and other properties of the filament at various temperatures.

Each route through the data analysis forces us to make certain compromises and estimates and it will be interesting to see how the various results compare. We will also be making a number of graphs and these will highlight other aspects of the problem.

A. **Power:** Calculate the power output of the bulb using $P = IV$.

(Record these values in the 4th column of both data tables.)

B. **Resistance:** Calculate the resistance of the filament at each voltage using Ohm's law.

(Record the resistance values in the 5th column of both data tables.)

C. **Resistivity:** Calculate the resistivity of the filament at each voltage using $R A_x / L = \rho$

(Record the resistivity values in the 6th column of both data tables.)

D-1. Temperature:

From the attached graph of the T (K) vs Resistivity we can derive the following approximate relationship between the room temperature resistance of tungsten and its temperature at any other known resistance, as follows:

$$T / T_0 = (R / R_0)^{0.82984}$$

Since the reference resistance and temperature are already known, and since you've measured the resistance's at the other temperatures, you should be able to find the temperatures at which those other measurements were made.

(Enter the calculated temperatures into the seventh column of Data Table I.)

D-2. Temperature:

(Enter the standard value for σ into Data Table III along with an assumed value for the emissivity of 0.5. We will use these to solve for the temperatures without resorting to outside data.)

Use the Stefan-Boltzman Law and the values already in that table to solve for the temperature at each voltage.

(Enter these temperatures into the seventh column of Data Table III.)

E-1. The Stefan-Boltzman Constant: From the data in Data Table II construct a plot of Power vs T^4 . It should yield a straight line with slope equal to $\sigma e A$. Select only the data points for temperatures above 1000 K and determine the slope of the best straight line through the data.

Use the slope of your fitted line and the surface area to solve for σe .

$$\sigma e = \text{_____} \text{ W/m}^2\text{K}^4$$

(Enter this value for σe into the appropriate line in Data Table I.)

Since we can only solve for the product of these two numbers, the best we can do from here is see if the product is reasonable. For example, the accepted value of σ is $5.6687 \text{ E}(-8) \text{ watts/m}^2\text{K}^4$. Use that value to solve for e .

$$e = \text{_____}$$

Values of e near 0.5 would be considered reasonable.

On the other hand, if we assume that e has a reasonable value of 0.5, what value of σ do you get?

$$\sigma = \text{_____}$$

How close are these to their reasonable values? How good is your data?

Calculate the surface area of the Tungsten wire:

This will be the circumference x length = $2\pi rL$

Surface area of filament = _____ m^2

Now solve for the filament temperatures assuming emissivity, e , equals 1.000 and fill-in these temperatures in the data table.

- C. **Wavelength:** There is a relationship between the temperature of a hot object and the color it glows. As things get hotter, the wavelength of their brightest glow decreases in wavelength, gradually moving from infrared into the visible range, beginning with red and gradually adding the colors until the colors add to white.

The relationship here is expressed by the *Wien Displacement Law*:

$$\lambda_{\max} T = 2.897820 \text{ E}(-3) \text{ metersKelvin}$$

You can now calculate the peak emission wavelength for each temperature and record it in the data table.

- D. **Resistance:** Ohm's Law ($V=IR$) works in every case here. Calculate and record the resistance of the wire.

- E. **Resistivity** (ρ): The resistivity of a material increases with temperature. Calculate the resistivity for each case. Notice that the resistivity goes up with temperature. Construct a graph of resistivity (vertical) and temperature (horizontal). Set the origin of the temperature axis of the graph to zero kelvin.

What is the slope of the line? _____

What is the resistivity at zero kelvin? _____

What happens to the resistance as the temperatures approaches absolute zero?

What is the term that describes this resistance change? _____