Seeing the Light: The Physics and Materials Science of the Incandescent Light Bulb

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Dr. Lawrence D. Woolf
General Atomics
San Diego, CA 92121
Larry.Woolf@gat.com

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Correspondence to the National Science Education Standards (NSES)

This unit relates to the following NSES physical science content standards in grades 5-8:

Properties and Changes of Properties in Matter

- "A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of sample."
- "Substances react chemically in characteristic ways with other substances to form new substances (compounds) with different characteristic properties."
- Electrical circuits provide a means of transferring electrical energy when heat, light, sound, and chemical changes are produced."

Transfer of Energy

- "Energy is a property of many substances and is associated with heat, light, electricity, mechanical motion, sound, nuclei, and the nature of the chemical. Energy is transferred in many ways."
- "Heat moves in predictable ways, flowing from warmer objects to cooler ones, until both reach the same temperature."
- Electrical circuits provide a means of transferring electrical energy when heat, light, sound, and chemical changes are produced."

This unit relates to the following NSES physical science content standards in grades 9-12:

Conservation of Energy and the Increase in Disorder

- "The total energy of the universe is constant. Energy can be transferred by collisions in chemical and nuclear reactions, by light waves and other radiation, and in many other ways. However, it can never be destroyed."
- "Heat consists of random motion and the vibrations of atoms, molecules, and ions. The higher the temperature, the greater the atomic or molecular motion."
- Everything tends to become less organized and less orderly over time. Thus, in all energy transfers, the overall effect is that the energy is spread out uniformly. Examples are the transfer of energy from hotter to cooler objects by conduction, radiation, or convection and the warming of our surroundings when we burn fuels."

Interaction of Energy and Matter

- "In some materials, such as metals, electrons flow easily, whereas in insulating materials such as glass they can hardly flow at all."

Correspondence to the Benchmarks for Science Literacy

4E Energy Transformations

8th grade

- Energy cannot be created or destroyed, but only changed from one form to another.
- Energy in the form of heat is almost always one of the products of an energy transformation.

12th grade

- Whenever the amount of energy in one place or form diminishes, the amount in other places or forms increases by the same amount.
- Transformations of energy usually produce some energy in the form of heat, which spreads around by radiation or conduction into cooler places.

4G Forces of Nature

12th grade

- Different kinds of materials respond differently to electric forces. In conducting materials such as metals, electric charges flow easily, whereas in insulating materials such as glass, they can hardly move at all.

3C Issues in Technology

8th grade

- Technology has strongly influenced the course of history and continues to do so. It is largely responsible for the great revolutions in agriculture, manufacturing, sanitation and medicine, warfare, transportation, information processing, and communications that have radically changed how people live.

11A Systems

8th grade

- Thinking about things as systems means looking for how every part relates to others. The output from one part of a system (which can include material, energy, or information) can become the input to other parts. Such feedback can serve to control what goes on in the system as whole.
- Any system is usually connected to other systems, both internally and externally. Thus a system may be thought of as containing subsystems and as being a subsystem of a larger system.

12th grade

- Understanding how things work and designing solutions to problems of almost any kind can be facilitated by systems analysis. In defining a system, it is important to specify its boundaries and subsystems, indicate its relation to other systems, and identify what its input and output are expected to be.

1C The Scientific Enterprise

8th grade

- No matter who does science and mathematics or invents things, or when or where they do it, the knowledge and technology that result can eventually become available to everyone in the world.

12th grade

- Progress in science and invention depends heavily on what else is happening in society, and history often depends on scientific and technological developments.
- Science disciplines differ from one another in what is studied, techniques used, and outcomes sought, but they share a common purpose and philosophy, and all are part of the same scientific enterprise. Although each discipline provides a conceptual structure for organizing and pursuing knowledge, many problems are studied by scientists using information and skills from many disciplines. Disciplines do not have fixed boundaries, and it happens that new scientific disciplines are being formed where existing ones meet and that some subdisciplines spin off to become disciplines in their own right.

8B Materials and Manufacturing

8th grade

- The choice of materials for a job depends on their properties and how they interact with one another. Similarly, the usefulness of some manufactured parts of an object depends on how well they fit together with other parts.
- Manufacturing usually involves a series of steps, such as designing a product, obtaining and preparing raw materials, processing the materials mechanical or chemically, and assembling, testing, inspecting, and packaging. The sequence of these steps is also often important.
- Modern technology reduces manufacturing costs, produces more uniform products, and creates new synthetic materials that can help reduce the depletion of some natural resources.

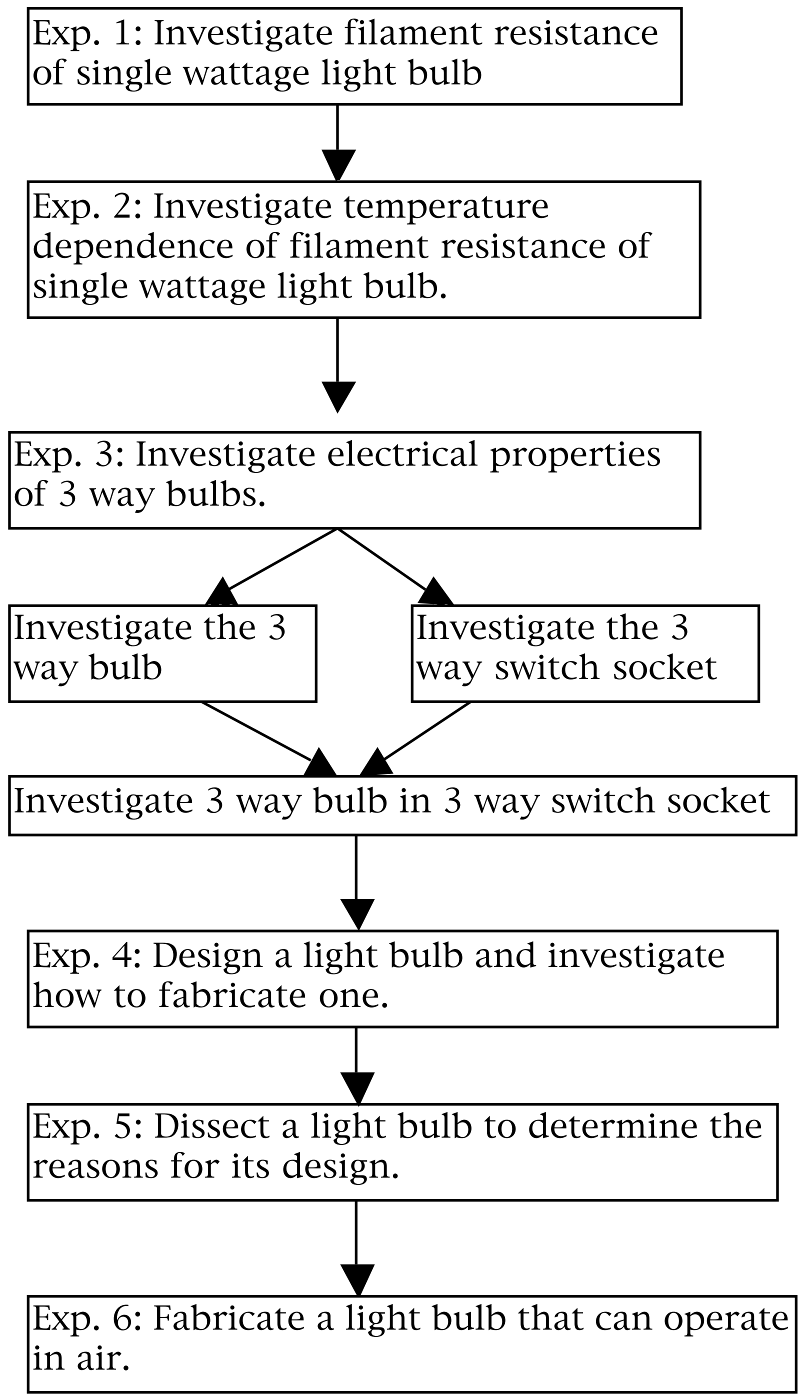
12th grade

- Scientific research identifies new materials and new uses of known materials.
- Manufacturing processes have been changed by improved tools and techniques based on more thorough scientific understanding, increases in the forces that can be applied and the temperatures that can be reached, and the availability of electronic controls that make operations occur more rapidly and consistently.

Acknowledgement

I would like to thank Professor Harvey S. Leff of the Cal Poly Pomona physics department for many helpful suggestions and comments.

Logical Construction of Module



Introduction

The development of the incandescent light bulb by Thomas Edison initiated the electrification of modern society and revolutionized the world. This module is intended to introduce the history, fabrication, materials and physics of light bulbs to high school students. Concepts such as Ohm's law, electrical power, energy conservation, electrical resistance and resistivity and blackbody radiation can be enhanced using this unit. Parts of this unit can be tailored for middle school use.

Basic Physics

When a light bulb is turned on using a switch, a constant (ac) voltage V of 120 volts is applied across the filament. Since the filament has a high resistance, because of its fine diameter and long length (see equation 4 below), a small amount of current flows through the filament according to Ohm's law

$$I = \frac{V}{R}, \quad (1)$$

where I is the current through the filament, V is the voltage across the filament and R is the resistance of the filament.

The filament then becomes hot, since the amount of power P produced in the filament is

$$P = \frac{V^2}{R}. \quad (2)$$

It is important to note that since the voltage is a constant in our electrical distribution system, the form of the equation for the power dissipated in a resistor should be that shown in equation 2, and should not be $P=I^2R$. Since V is a constant, equation 2 relates one variable - R - to another variable - P. If the equation $P=I^2R$ was used, then P, I, and R would all be variables.

All objects emit radiation, which was first correctly described by the German physicist Max Planck. The total power emitted per unit surface area (S) of a hot object at a temperature T (in degrees Kelvin) is given by the Stefan-Boltzmann law:

$$\frac{P}{S} = \varepsilon\sigma T^4, \quad (3)$$

where the constant σ, called the Stefan-Boltzmann constant, has the value 5.67×10^{-12} $W/(cm^2\text{-}K^4)$. The emissivity of the material ε is a material dependent quantity that can be looked up in a handbook. For tungsten, the value of ε is about 0.3. Note that the symbol σ is also used to represent the electrical conductivity of a material, so that care must be taken in its use so that confusion does not result.

Now for a long cylindrical filament of radius r and length L, the cross sectional area A is πr^2 and the surface area S is $2\pi rL$ (ignoring end effects). Recall that the electrical resistance R of material is given by

$$R = \frac{\rho L}{A}, \quad (4)$$

where ρ is the electrical resistivity of the material. For tungsten at room temperature, the value of ρ is 5.7×10^{-6} ohm-cm.

The final equation that will be used in this unit is the equivalent resistance of 2 resistors in parallel or series. For 2 resistors of resistance R_1 and R_2, the equivalent resistance of their parallel combination R_p is

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} \quad \text{or} \quad R_P = \frac{(R_1 \times R_2)}{(R_1 + R_2)}. \quad (5)$$

For 2 resistors in series, the equivalent resistance of the series combination R_S is

$$R_S = R_1 + R_2. \quad (6)$$

Equations 1- 6 form the basis for the all of the calculations performed in this unit.

Advanced Topic

Combining equations 2 and 4, we find that the power dissipated in the filament can be written as

$$P=\frac{V^2\pi r^2}{\rho L}. \quad (7)$$

Since the voltage in our houses is fixed, it is apparent from equation 2 that for higher wattage bulbs, the electrical resistance of the filament must decrease as the wattage increases. From equation 4, R can be decreased by increasing A (i.e. r^2) or by decreasing L. Therefore, for higher wattage bulbs, it is necessary to either increase r or decrease L. This may also be seen from equation 7. Since the power will increase as the square of r and only as 1/L, it is simpler to just increase r. Also, it is preferable to increase r since this increases the surface area of the filament. Note that decreasing L decreases the surface area of the filament. This is evident in table 1 below.

From the Stefan-Boltzmann law, the power emitted by the filament can also be written as

$$P=\varepsilon\sigma T^4(2\pi rL). \quad (8)$$

From this equation, we can see that the bulb wattage (brightness), filament temperature (lifetime), filament radius and length are all interdependent. As noted above, it is desirable to maximize the surface area of the filament by increasing r. As can be seen from equation 8, if the power is increased, it is desirable to increase r and L to minimize the increase in T. This is because higher temperatures reduce the lifetime of the filament (although increasing its light output).

From energy conservation considerations, the power dissipated in the filament (power input) must equal the power emitted by the filament (power output). (This neglects other energy loss mechanisms). Therefore equations 7 and 8 can be equated. After some algebra we find that

$$T^4=\frac{V^2 r}{2\varepsilon\sigma\rho L^2} \quad (9)$$

Equation 9 demonstrates the interdependence of the filament temperature and the filament radius and length.

Introduction to Filament Design Parameters: Background Material for Teachers

Filament diameters and lengths for different wattage light bulbs are shown in the table below. Don't disclose the length of the filament to your students! They will discover it by calculating this number shortly and they will also determine it experimentally. The values in table 1 below were obtained from a GE light bulb brochure.

Table 1: Filament Diameter and Length for Different Wattage Bulbs

Bulb Wattage (W)	Filament Diameter (cm)	Uncoiled filament length (cm)
25	0.0030	56
40	0.0033	38
60	0.0046	53
75	0.0053	55
100	0.0064	58
200	0.0102	72

(For a 60 W bulb, the length of the filament is 53 cm long. The filament, as will be seen later in the dissection experiment, consists of a coiled coil. After the first coiling, the filament length is 8.3 cm and consists of 1100 turns. This coil is then coiled again so that its final length is only 2.0 cm long!)

Let's calculate the resistance of the filament in two different ways from the table above. *Note that the resistance that we are calculating is the resistance of the filament when it is on, i.e. when it is hot.* The electrical resistivity of tungsten at the operating temperature of about 3000 K (2700 C) is about 8.6×10^{-5} ohm-cm or 15 times its room temperature value. Recall that the resistance of metals increases with increasing temperature. This value is to be used in the calculation of the last column below.

Table 2: Filament Resistance When the Bulb is On Calculated in 2 Ways for Different Wattage Bulbs

Bulb Wattage (W)	R (ohms)= $\frac{V^2}{P}$	R (ohms) = $\frac{\rho L}{A}$
25	576	681
40	360	382
60	240	274
75	192	214
100	144	155
200	72	76

To demonstrate in detail how these values were determined, we show the 100 W calculation in detail below.

$$R = \frac{V^2}{P} = \frac{(120\ V)^2}{100\ W} = 144 \text{ ohms.}$$

$$R = \frac{\rho L}{A} = \frac{(8.6 \times 10^{-5} \text{ ohm-cm}) \times (58 \text{ cm})}{\pi(0.0032 \text{ cm})^2} = 155 \text{ ohms.}$$

Note that the values are in relatively good agreement except for the 25 W filament resistance. This suggests that the 25 W filament runs at a somewhat lower temperature than the other bulbs, since then its electrical resistivity would be lower.

The resistance of the filament increases by about a factor of 15 between room temperature and 3000 K. Therefore the room temperature resistance of the filament should be 144 ohms/15 = 9.6 ohms for a 100 W bulb.

Experiment 1:
The Room Temperature Filament Resistance of Different Wattage Light Bulbs

Purpose:

Determine the relationship between the wattage of a light bulb and the measured value of the filament resistance.

Materials Needed:

1. Ohmmeter - digital auto-ranging preferred, such as the VWR P/N 26983-175
2. 100 W light bulb
3. Optional - other wattage light bulbs

Procedure:

1. Measure the resistance of the filament of the 100 W (or other) light bulb by connecting one of the probes of the ohmmeter to the bottom contact of the bulb and the other probe to the side of the base of the bulb. This will measure the resistance of the filament, which dominates the resistance being measured.
2. Determine the resistance of the filament using the equation relating the wattage of the bulb to the filament resistance.
3. Discuss why the value of the resistance determined experimentally in step 1 differs from that obtained theoretically in step 2.
4. Optional. Repeat steps 1-3 for other wattage bulbs.
5. Determine the length of the filament from the room temperature resistance of the filament, using the equation:

$$L = \frac{RA}{\rho}.$$

Use the value for the room temperature electrical resistivity of tungsten of $\rho = 5.7 \times 10^{-6}$ ohm-cm. Use a value for the diameter of the filament of 0.0064 cm.

6. Discuss how the calculated length of filament might be contained in the bulb.

Teacher's Guide to Experiment 1

1. The measured value of the resistance of the 100 W bulb filament should be about 9.6 ohms.

2. The equation relating the wattage of the bulb to the filament resistance is:

$$P = \frac{V^2}{R} \quad \text{or} \quad R = \frac{V^2}{P}.$$

Since P = 100 W and V = 120 V, then $R = \frac{(120\ V)^2}{100\ W} = 144$ ohms.

Note that when V stands alone, it represents the voltage. When V appears after a number, it represents the unit of volts.

3. The resistance determined experimentally is the resistance when the filament is at room temperature. At room temperature the bulb is off, no current is flowing through the filament and no power is being dissipated in the filament. The resistance determined theoretically is the resistance when the filament is dissipating 100 W of power, i.e.. it is on and the filament is hot. The resistance of a metal increases as it gets hotter. In this case, the resistance when the filament is hot is 15 (144 ohms/9.6 ohms) times higher than when it is at room temperature.

(Optional: If an ammeter or a shunt resistor and a voltmeter are available, measure the resistance of the filament when the bulb is on by measuring the current I through the filament to determine the resistance using Ohm's Law: R = 120 V/ I)

5. $L = \frac{RA}{\rho} = \frac{(9.6\ \text{ohms})(\pi)(0.0032\ \text{cm})^2}{5.7 \times 10^{-6}\ \text{ohm-cm}} = 54$ cm

6. The students should realize that the filament length of 54 cm is much longer than the bulb, so that the filament must be folded or coiled in some way. As they will see in the light bulb dissection experiment, the filament consists of a coiled coil of tungsten wire.

Advanced Topic for Answer 5.

The length of the filament can also be estimated in one other way. Equating P in equations 2 and 3, we obtain for the total emitting surface area of the filament:

$$S = \frac{V^2}{\varepsilon \sigma R T^4}.$$

Recall that at the operating temperature of about 3000 K, the filament resistance of a 100 W bulb is about 121 ohms. Therefore,

$$S = \frac{(120 V)^2}{0.3 \times 5.67 \times 10^{-12} \text{ W-cm}^{-2}\text{-K}^{-4} \times 121 \text{ ohms} \times (3000 \text{ K})^4}$$

$$S = 0.86 \text{ cm}^2$$

For a long cylindrical wire, $S = 2\pi r L$ and $r = 0.0032$ cm for a 100 W bulb so

$$L = \frac{S}{2\pi r} = \frac{0.86 \text{ cm}^2}{2\pi \times 0.0032 \text{ cm}}$$

$$L = 43 \text{ cm}$$

which is fairly close to the value of 54 cm determined above from the room temperature properties.

Experiment 2:
The Temperature Dependence of the Resistance of a 100 W Light Bulb

Purpose:

To investigate the relationship between the temperature of the filament of a light bulb and its resistance.

Materials Needed:

1. Ohmmeter - digital autoranging preferred, such as the VWR P/N 26983-175
2. 100 W light bulb

Procedure:

1. Insert the 100 W light bulb in a lamp socket, turn on the lamp and keep it on for about 5 minutes or more.
2. Unplug the lamp and using the two flat prongs on the cord plug and the ohmmeter, measure the resistance of the 100 W light bulb filament as it cools. Record the resistance every 5 seconds for 1 minute and then every 10 seconds for the next minute or more.

(Note that the lamp will remain hotter for longer if the bulb is placed in a vertical position with the bulb housing over the bulb. In this position, the heat is trapped more than in other positions. To keep the lamp even hotter for longer **after unplugging the lamp**, place a fireproof pad (such as an oven glove) over the lamp housing to trap the heat so that the bulb will cool down at a slower rate.

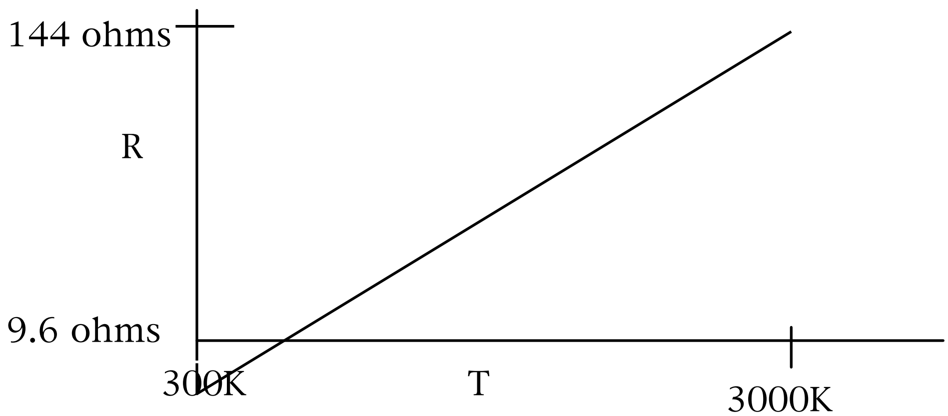
3. Use the results of experiment 1 to convert the measured values of resistance to temperature. Assume that the resistance varies linearly with temperature and that the temperature of the filament when it is on is 3000 K or about 2700 C.
4. Plot the filament temperature as a function of time as it was cooling.

Teacher's Guide for Experiment 2

1. Keep the bulb on until it gets hot to the touch.

2. Since the filament has the greatest resistance in the circuit, the filament resistance can be measured by measuring the circuit resistance at the prongs.

3. In experiment 1, the filament resistance at room temperature was determined to be about 9.6 ohms and about 144 ohms at 3000 K (the temperature of the filament when the lamp is on.) So the filament resistance R and the filament temperature T are related as shown in the graph below (assuming a linear dependence which is a good approximation). Using this graph or the linear relationship between R and T, the measured values of the resistance of the filament can be converted to temperature.



4. From 2, values of R vs time were measured. From 3, values of R vs T were determined. Using these two data sets, values of T vs time (the filament cooling curve) can be determined.

Note that there are two other ways to demonstrate that the filament resistance increases with increasing temperature

- Measure the resistance of the bulb as you warm it by holding it in your hands.
- Attach a copper wire to each of the lamp socket screws. Place the bulb and lamp socket in an oven at about 350 F or 200 C and snake the copper leads out of the oven and attach them to an ohmmeter.

Experiment 3:
The Electrical Properties of 3-Way Bulbs

Purpose:

To determine how a 3 way light bulb works.

Materials Needed:

1. Ohmmeter - digital autoranging preferred, such as the VWR P/N 26983-175
2. 50 W - 100 W - 150 W 3-way light bulb (or other type of 3 way light bulb)
3. 3 way switch socket (available at any hardware store, such as Home Depot)

Procedure:

1. Find the three electrical contacts on the base of the light bulb. Measure the electrical resistance between each of the 3 combinations of contacts. The connections are best made by contacting the ohmmeter probes to the silver blobs of solder. Note that one contact is the silvery dot on the bottom (contact 1), one is the copper colored annular disk surrounding the bottom dot (contact 2)), and one contact is the silvery threads on the side of the bulb (contact 3) .

2. Calculate the expected room temperature resistance of a filament for a 50 W bulb, a 100 W bulb and a 150 W bulb. Use the theoretical method described in experiment 1, steps 2 and 3.

3. Compare the experimentally determined values obtained in the first step of the procedure with the theoretically determined values in the second step of the procedure. What conclusions can be drawn? Can you determine which filaments are between which contacts? Draw a diagram showing your results.

4. Place the 3 way bulb in the socket. When they are used, 120 V is applied across the 2 screw terminals of the socket. Measure and record the resistance across the 2 screw terminals in the four different positions of the switch. You may also wish to examine how the switch works to obtain additional information.

5. Compare these data with the data above. What conclusions can you draw regarding what filaments are on when the switch is in the different positions?

Teacher's Guide to Experiment 3

1. The measured electrical resistances are

contact 1 to contact 2 R = 35 ohms
contact 2 to contact 3 R = 21 ohms
contact 1 to contact 3 R = 11 ohms

2. a. 50 W bulb

When it is on, the hot filament resistance can be determined using $R = V^2/P$ so $R = (120\ V)^2/50\ W = 288$ ohms.

The room temperature resistance is 15 times smaller, so the expected room temperature resistance is 288 ohms/15 = 19 ohms.

b. 100 W bulb

When it is on, the hot filament resistance can be determined using $R = V^2/P$ so $R = (120\ V)^2/100\ W = 144$ ohms.

The room temperature resistance is 15 times smaller, so the expected room temperature resistance is 144 ohms/15 = 9.6 ohms.

c. 150 W bulb

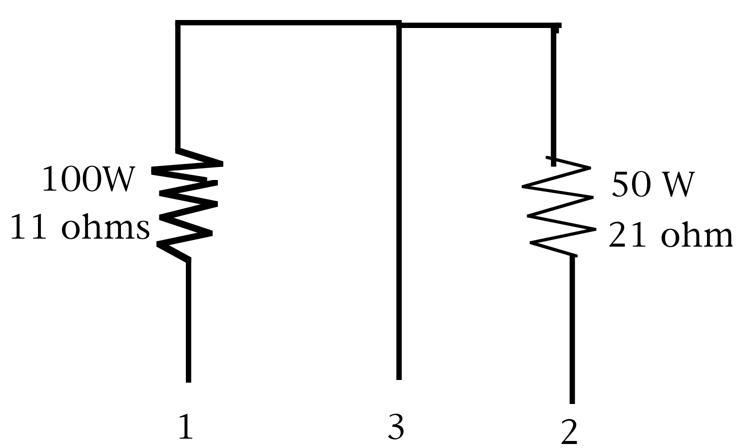
When it is on, the hot filament resistance can be determined using $R = V^2/P$ so $R = (120\ V)^2/150\ W = 96$ ohms.

The room temperature resistance is 15 times smaller, so the expected room temperature resistance is 96 ohms/15 = 6.4 ohms.

3. The 50 W filament is electrically connected to contacts 2 and 3 because 21 ohms is almost the same as 19 ohms - they are the same within experimental uncertainties.

The 100 W filament is electrically connected to contacts 1 and 3 because 11 ohms is almost the same as 9.6 ohms - they are the same within experimental uncertainties.

The electrical resistance between contacts 1 and 2 (35 ohms) is almost the same as the sum of the electrical resistance between contacts 1 and 3 (11 ohms) and contacts 2 and 3 (21 ohms). So contacts 1 and 2 must be connected across the series combination of the 50 W and the 100 W filaments.



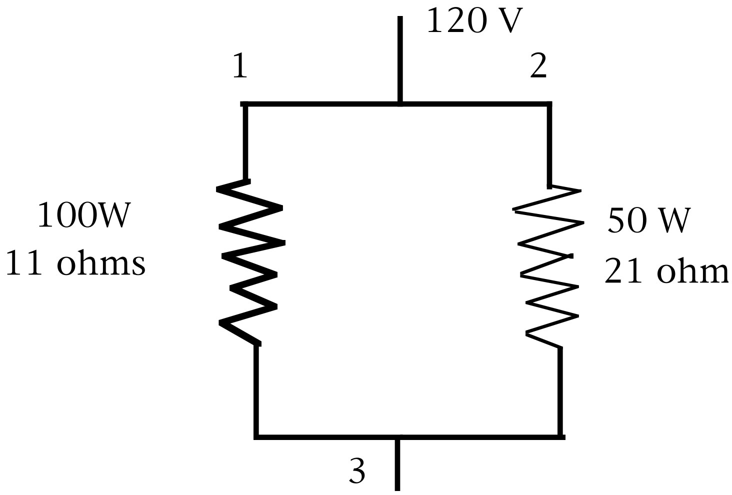
4. switch position 1 R = open
   switch position 2 R = 23 ohms
   switch position 3 R = 11 ohms
   switch position 4 R = 8.2 ohms

5. In switch position 1, no voltage is applied to any of the filaments.

In switch position 2, 120 V is applied across contacts 2 and 3 (the 50 W, 21 ohm resistor) because 23 ohms is just slightly higher than the 21 ohms measured across positions 2 and 3 previously. The switch apparently contributes a couple of ohms of series resistance.

In switch position 3, 120 V is applied across contacts 1 and 3 (the 100 W, 11 ohm resistor) because 11 ohms is in agreement with the previously measured resistance across positions 2 and 3. The switch apparently contributes almost no series resistance in this position.

In switch position 4, 120 V is applied across the parallel combination of the 50 W and 100 W filaments. In other words, 120 V is applied to contacts 1 and 2 and contact 3 is ground, as shown below.



This can be determined in 2 ways. First, note that the parallel combination of the 2 resistances of 11 ohms and 21 ohms is

$$R_P = \frac{(R_1 \times R_2)}{(R_1 + R_2)} = \frac{21 \text{ ohms} \times 11 \text{ ohms}}{32 \text{ ohms}} = 7.2 \text{ ohms.}$$

The value of 7.2 ohms is very close to the value of the resistance measured when the switch was at position 4 of 8.2 ohms. Apparently, the switch contributes about 1 ohm of resistance in this position.

The second way that this can be determined is by examining the switch itself using the ohmmeter. In switch position 4, the switch terminals inside the housing, which connect to contacts 1 and 2 on the bulb, are shorted together and are connected to one of the screw terminals. The other screw terminal is connected to the threaded part of the housing, which in turn electrically connects to contact position 3 on the bulb.

In fact, the second screw terminal is always connected to the threaded part of the housing, which is connected to contact position 3 on the bulb. Note that the first screw terminal is connected to the following contacts as the 3-way switch is turned:

- switch position 0 (off) - no contact
- switch position 1 - connected to contact 2
- switch position 2 - connected to contact 1
- switch position 3 - connected to contacts 1 and 2.

Advanced Topic

You might point out to the students that a 4 way bulb is possible by utilizing the series equivalent of the filaments, by using contacts 1 and 2 only. In this case the bulb wattage would be

$$P = \frac{V^2}{R} = \frac{(120\ \text{V})^2}{288\ \text{ohms} + 144\ \text{ohms}} = 33.3\ \text{W}.$$

Note that the highest wattage of a 3-way bulb is always the sum of the 2 lower wattage settings. The reason is that at the highest setting, 120 V is applied across both of the filaments, so that the light output is the sum of the filaments at the two lower settings.

It is interesting to note that if our electrical system operated on constant current instead of constant voltage, the three way bulb would place the filaments in series in the highest wattage setting. Along this line of thought, you might ask your students to consider what an electrical distribution system would be like if it operated on constant current instead of constant voltage.

Let's review this topic in a slightly different way. If we have a constant voltage system and we want to make a 3-way light bulb where the power produced at the highest setting P is the sum of the power produced at the 2 lower settings: P_1 and P_2 using resistors R_1 and R_2, then

$$P = P_1 + P_2 = \frac{V^2}{R_1} + \frac{V^2}{R_2} = V^2 \left[\frac{1}{R_1} + \frac{1}{R_2}\right].$$

So the resistors should be arranged in parallel.

If instead we have a constant current system and we want to make a 3-way light bulb where the power produced at the highest setting P is the sum of the power produced at the 2 lower settings: P_1 and P_2 using resistors R_1 and R_2, then

$$P = P_1 + P_2 = I^2R_1 + I^2R_2 = I^2 [R_1 + R_2].$$

So the resistors should be arranged in series.

Experiment 4:
Light Bulb Design

Purpose:

To design a light bulb based on basic material and design parameters. Both the materials and the method of fabrication will be explored by the students. This experiment should be done in teams of 3 - 5 students.

Materials Needed:

1. Creative brain
2. Pencil and paper

Procedure:

In this experiment, students will design a light bulb and describe the construction steps necessary to fabricate a light bulb using the information below.

1. Materials glow brighter at higher temperatures and must be heated to above 2000 C to produce significant amounts of visible light. Materials that can withstand these high temperatures are expensive. Some candidates are shown in the table below.

Filament Material	Melting Point (C)
Platinum	1773
Osmium	2700
Tantalum	2900
Tungsten	3380
Carbon	3600

2. The more power dissipated in a material, the brighter it will glow.
3. The resistance of a material is proportional to its length and inversely proportional to its cross sectional area.
4. Most materials that conduct electricity oxidize and disintegrate at high temperatures in the presence of oxygen or air.
5. Glass can be easily formed to different shapes, and can be sealed to itself and to other metals by heating to relatively low temperatures.

Teacher's Guide to Experiment 4

This experiment has many possible answers. The students should write up a design and fabrication sequence for a light bulb that meets the following goals:

1. It is clearly written.
2. The filament material operates in a vacuum or inert gas.
3. A glass bulb contains the filament and its inert or vacuum atmosphere.
4. The filament should be the most resistive part of the circuit.
5. The filament consists of a material with a high melting point.
6. The fabrication steps are clearly described or diagrammed and are arranged in order.

See the GE booklet about the light bulb for the actual method and materials used to fabricate light bulbs.

Experiment 5: Light Bulb Dissection

Purpose:

To dissect a light bulb, examine the materials used in its fabrication, and understand the reason for the design and the use of the materials.

Materials Needed:

1. Light bulb - 100 watt or 3 way.
2. Hammer
3. Newspaper
4. Safety goggles
5. Gloves

Procedure:

In this experiment, students will dissect a light bulb to investigate how a light bulb is constructed. *This experiment will be more successful if the light bulbs first are turned on for about 10 minutes - the students could do this at home*. (As it is fabricated, the wire in a light bulb filament is drawn through a die and then bent into shape. At this point the wire is very brittle. When the wire is first turned on and heated up, it quickly anneals. In this state, the wire is still fairly strong, but it is much more ductile.)

The students should carefully break open a bulb by hitting it with a hammer, with the bulb encased in few sheets of newspaper. They should also wear safety glasses and thick gloves. Break off any sharp protruding pieces of glass with the hammer. ***This should be done under close supervision.*** Different types and wattages of bulbs as well as 3 way bulbs could also be dissected. Dissecting a 3 way bulb will be particularly informative if the students have already performed experiment 2.

Have them identify and describe the optical, thermal, electrical and material requirements for each of the components.

1. The filament
2. The bulb
3. The base
4. The lead wires that connect to the filament
5. The two welds where the lead wires are connected to the base
6. The exhaust tubing
7. The flare

Teacher's Guide to Experiment 5

1.Very high temperature capability, high resistivity.

Note, by looking carefully or through a magnifying glass or a microscope that the filament actually consists of a coiled coil of wire. It is easiest to see this near the end of the coil where it is connected to the lead wire. See Fig. 4 for a photograph of a section of coiled coil wire.

Now they can observe how a long length of filament can be contained in a such a small space. Have your students try to determine the length of the filament by estimating the diameter of each of the coils and estimating the number of turns. Recall that earlier we determined that the length of the filament was about 45 cm.

Note the similarity of the 3 way bulb filament design to the figure in the 3 way bulb section.

2. Transparent, cheap, formable at low temperatures.
3. Electrically conductive, cheap.
4. Electrically conductive, chemically and thermal expansion compatible with glass.
5. Electrically conductive.
6. Sealable at low temperatures.
7. Sealable at low temperatures.

Also note that the coating on the inside of the glass bulb is a dry white (silica or SiO_2) powder coating held on electrostatically to the glass, which can be wiped away to expose the clear glass.

See the attached appendix 2: The Extraordinary Light Bulb...Its parts and assembly, a GE publication, for information about the components of the light bulb and how they are assembled. Note that not all bulbs have the support wire. An interesting historical note: initially the pump out tube for the glass bulb was on top of the bulb, but this was considered unsightly. Notice that the pump out tube is not visible in the current design.

Also note that wires directly attached to the tungsten filament must have cross sectional area sufficiently large so that their resistance is much less than the filament. On the other hand, the cross sectional area must not be too large or the heat leak down these leads will be so great that the filament temperature will be much lower, leading to less light output and lower bulb efficiency.

Experiment 6:
Light Bulb Fabrication

Purpose:

To fabricate a light bulb that can operate in air.

Materials Needed:

1. Variac transformer or dc power supply or batteries
2. Copper leads
3. 0.010 inch diameter Kanthal AF wire
4. 0.003 inch diameter Kanthal AF wire

Procedure:

The teacher or ***closely supervised*** students will build a simple light bulb using materials contained in this kit. ***This experiment is potentially dangerous so appropriate precautions must be taken.***

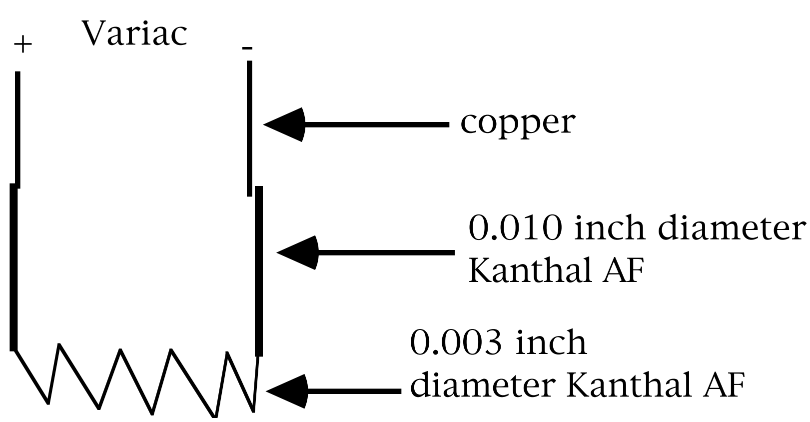
1. First, you will need a Variac transformer (preferred) or a dc power supply or batteries.

2. Connect the copper leads (use standard hook up wire or strip a power cord) from the Variac to the 0.010 inch diameter Kanthal AF leads by twisting the ends together.

3. Connect the 0.010 inch diameter Kanthal AF wires (like the lead wires in the light bulb) to the 0.003 inch diameter Kanthal AF wire (like the tungsten filament in the light bulb) by twisting the ends together.

4. By increasing the Variac voltage, the current to the 0.003 inch diameter Kanthal AF filament can be increased to resistively heat the filament and cause it to glow. For a filament about 20 cm long, a voltage of about 40 V is required. This can be done in air because the Kanthal AF wire is oxidation resistant.

Caution: This experiment should be done by the teacher or under close supervision. During this experiment these exposed wires are at potentially dangerous voltages and currents.



The electrical resistivity of the Kanthal AF wire is 1.4×10^{-4} ohm-cm at essentially all temperatures. This is quite different than the behavior of pure metals such as copper or tungsten, where the electrical resistivity increases significantly as the temperature increases. Have your students determine the electrical resistance of the Kanthal AF wire filament by calculation (using equation 4) and by measurement with the ohmmeter.

Application note: This experiment can be used to simulate the principle of a **hot wire anemometer**, a device for measuring the speed of a gas. In an anemometer, a very thin wire, usually made out of platinum, a nonreactive high melting point material, is exposed to a stream of gas and is heated well above the temperature of the gas by the passage of an electric current. The flowing gas cools the wire at a rate proportional to the speed of the gas flow, thus lowering the temperature of the wire. As noted earlier in this module, the resistance of the wire is a function of its temperature, decreasing as the wire temperature decreases (which is also the principle of a platinum resistance thermometer). The anemometer can be operated at a fixed current, with the voltage drop along the length of the wire being measured to determine how the electrical resistance changes. Hot wire anemometers can measure gas speeds ranging from 0.15 m/s to supersonic speeds and are capable of detecting rapidly varying speed changes.

To simulate the hot wire anemometer, just place a multi-speed fan near the Kanthal filament when it is on. First note the filament color (or if the appropriate equipment is available, measure the resistance of the filament) with the fan off. Now, turn the fan on and note the color (or measure the resistance) of the filament. As it cools, it changes color. Examine the color when the fan is on the higher settings. Note that the color of the wire (or the resistance of the filament) is a measure of the speed of the air flow.

Advanced Topic: Oxidation Resistant Materials

Why can't tungsten wires be used for the light bulb fabrication experiment? If the filaments are still intact from the light bulb dissection experiment, turn on the light bulb after screwing it into a socket. The filament will not last for long. You will see a puff of smoke given off by the filament - this is the tungsten oxide forming and vaporizing. Be sure to stay away from the smoke - do not breathe it. The reason is that the tungsten rapidly oxidizes when it is heated - in general, the oxidation rate of a material increases as the temperature is increased. These oxides of tungsten vaporize at temperatures below about 1500 C. (See the CRC Handbook of Chemistry and Physics.) They are therefore quite unstable in the presence of oxygen at the temperatures required for significant light output (>1000 C) from a filament.

This is quite different behavior from that exhibited by the Kanthal AF wires used in the light bulb fabrication experiment above. These wires are used in kilns in which ceramics are fired.

Oxidation resistant behavior is also exhibited by nichrome heater wires typically used for heater elements in electric stoves, ovens, toaster ovens, toasters, hair dryers and space heaters. These nichrome wires are heated to red hot temperatures of about 600-800 C, where the air passing by them is heated either by conduction or convection.

The Kanthal AF wires are extremely oxidation resistant even at temperatures near their melting point of 1500 C. These wires are composed of mostly iron (72%), with some chromium (22%) and aluminum (6%). As this wire is heated up, it becomes covered with the thermodynamically most stable oxide. Since aluminum oxide is more thermodynamically stable that either chromium oxide or iron oxide, a layer of aluminum oxide forms on the surface of this wire.

How does this layer of aluminum oxide prevent oxidation of the remainder of the wire? The answer is that the diffusion rate of oxygen through aluminum oxide is very slow and it takes a long time for oxygen atoms from the outside to diffuse through the already formed aluminum oxide layer to the unoxidized Kanthal AF material underneath. An example of the microstructure of a section of Kanthal wire that has had 30 micrometers of its surface oxidized to form aluminum oxide is shown in Fig. 5.

Let's calculate how long it will take for oxygen atoms to diffuse through a layer of alumina that is L=30 micrometers thick. The diffusion rate D is temperature dependent and at 1200 C is about $D=10^{-16}$ cm^2/sec. The time t for an atom to travel through a thickness L if its diffusion rate is D is given by:

$$t = \frac{L^2}{D}. \quad (10)$$

Therefore, it will take $(3 \times 10^{-3}\ cm)^2/(10^{-16}\ cm^2/sec) = 9 \times 10^{10}$ sec = 10^6 days. This very long time indicates that the material under the oxide layer will take a long time to oxidize and hence will be very stable.

The Nichrome wires are also quite oxidation resistant. They consist of about 80% nickel and 20% chromium, with a melting point of about 1400 C. Since chromium oxide is more stable than nickel oxide, a layer of chromium oxide will form on the surface of the nichrome wire when it is heated up. The wire is stable at high temperatures because the diffusion rate D of oxygen through chromium oxide is also very low at high temperatures: at 1200 C, $D = 10^{-14}$ cm^2/sec. Oxygen diffusion rates through nickel oxide and iron oxide are much higher than those of chromium oxide and aluminum oxide.

Advanced Topic:
Blackbody Radiation

The classical theory of physics predicted that the power given off by a blackbody would be infinite. Thus, this prediction of classical physics, known as Rayleigh's law, was absolutely unable to describe the distribution of light from a blackbody. Planck examined the experimentally known blackbody curve that described the frequency dependence of the intensity of the radiation and empirically determined the form of the equation that fit the data. Then, in 1900, he found a simple derivation for the equation that involved the peculiar assumption that the energy levels of the blackbody that give off the radiation can only occur in discrete and equally spaced intervals. In other words, these energy levels were not continuous, but instead were quantized. His was the first correctly determined quantum mechanical formula and it gave birth to quantum mechanics and led to the demise of classical mechanics.

According to Planck's formula:

1. A blackbody at any temperature emits some radiation at all wavelengths, but not in equal amounts.
2. A hotter blackbody emits more radiation per unit area at all wavelengths than does a cooler blackbody.
3. A hotter blackbody emits the largest proportion of its energy at shorter wavelengths than a cooler blackbody does. This can be described quantitatively by Wien's law, which states that the wavelength at which a blackbody emits its maximum amount of radiation, λ_{max} times the temperature equals a constant or

$$\lambda_{max}T = 2.90 \times 10^{-3} \text{ m-K.} \quad (11)$$

These ideas are schematically shown in Fig. 1.

Note that for a typical filament that operates at a temperature of 3000K, the maximum amount of radiation is emitted at a wavelength of 9.7×10^{-7} m or nearly 1 micrometer, which is in the infrared regime. Thus, most of the light emitted by the filament is in the infrared, not the visible wavelengths.

Advanced Topic: Filament Material

As is evident from Fig. 1, is desirable that the filament (blackbody) temperature be as hot as possible for two reasons. First, the amount of visible light emitted per unit of energy consumed is higher; in other words, the light is cheaper. Second, the color of the light is nearer to that of the sun, which is approximately a 6100 K blackbody, shown as the daylight curve in Fig. 2. The choice of materials that can operate at very high temperatures is limited: electric lamp filaments have been made from the following materials.

Filament Material	Melting Point (C)
Platinum	1773
Osmium	2700
Tantalum	2900
Tungsten	3380
Carbon	3600

Edison used platinum as the filament in his early lamp experiments. (Actually, he used a zirconium oxide coated platinum wire, with the zirconium oxide coating preventing the oxidation of the platinum.) However, he switched to carbon filaments due to the high cost, short lifetime and low light output of the platinum filament. In 1879, he produced a carbon filament lamp that remained lit for over 40 hours.

It is not practical to operate any filament at temperatures approaching its melting point, due to the high rate of evaporation at these temperatures. When evaporation occurs as a result of operating at high temperature, not only does the filament become thinner, resulting eventually in failure, but the evaporated material settles on the inside of the lamp causing it to darken. This deposit absorbs some of the light and, as it increases in thickness, the efficiency of the lamp decreases. Although the melting point of the carbon filament is very high, the rate of evaporation is so great that it cannot be operated at temperatures in excess of about 1850 C, where its efficiency is fairly low. The useful life of this type of lamp was more often terminated by excessive darkening of the bulb than by filament failure.

Tungsten increasingly was recognized as an ideal metal for a filament, but it was difficult to fabricate into fine wires. In 1910, Dr. William Coolidge announced that he had developed a commercial process for producing fine wires of tungsten. The Coolidge process is still used to produce today's tungsten wire filaments for incandescent lamps. These filaments operate at temperatures of about 2700 C. If the lamp operated at higher temperatures, it would give off more light and produce light more efficiently, but it would burn out sooner due to the higher evaporation rate of the tungsten at the higher temperature. Thus, filament design is a tradeoff between bulb lifetime and light output.

The filament wire must be very uniform in diameter. Since the same amount of current passes along its entire length, any thin spot will be hotter because of its higher resistance, as can be seen from equation 4. At such a hot spot increased evaporation will occur, leading to further thinning and hence higher resistance and still higher temperature. This effect leads to rapid failure of the filament: if the filament diameter at any point is only 1% less than specified, the lamp life may be reduced by 25 %.

The lamp designer must be aware that the resistance of metals generally increases with increasing temperature. Indeed, the filament resistance at the operating temperature is typically 15 times greater than its room temperature value. For a 100 W lamp filament, the typical resistance is about 9.6 ohms when at room temperature (so I=12.5 Amps) and 144 ohms at the operating temperature (where I=0.83 Amps). This leads to a large "inrush" current when the lamp is turned on, which must be accounted for by the designer.

As noted above, as the lamp operates, filament material evaporates and deposits on the inside of the bulb, darkening it and reducing its light output. Since the filament material is evaporating, the diameter of the filament decreases, increasing the filament resistance. It is interesting to point out that if the filament operates on constant current instead of constant voltage, the power dissipated in the lamp will increase ($P=I^2R$), so that the light output will increase over the lifetime of the lamp. This light output increase roughly counteracts the decrease in light output due to bulb blackening due to evaporation of filament material on the inside wall of the bulb, leading to a relatively constant light output over the life of the bulb. Many street lights operate on constant current.

Advanced Topic: Filament Environment

It is desirable to operate the filament at a high temperature, but the evaporation of the tungsten must be minimized to increase the lifetime of the filament and to prevent deposits of tungsten on the inside of the bulb, which darkens the bulb. Recall that evaporation is caused by some molecules of a substance having greater energies than others, thus enabling them to break away from the surface. This process can be hindered by placing molecules of another substance near the surface. This effect also causes water to boil at lower temperatures at high altitudes where the air pressure is lower, where the density of air molecules is lower, making evaporation easier. The evaporation from a tungsten filament can be reduced by filling the lamp bulb with an inert gas that will not cause oxidation of the filament. Typically, a mixture of nitrogen and argon is used.

The filling gas conducts some heat away from the filament, causing a reduction in efficiency. Most lamps above 25 W operate in a gas, because the lower rate of filament evaporation offsets the heat loss caused by the gas. Most lamps 25 W and below operate in a vacuum because the reduced heat loss offsets the higher rate of filament evaporation.

The filling gas is introduced into the lamps at slightly less than atmospheric pressure. When the lamp operates, the pressure rises to about atmospheric pressure, in accord with the ideal gas law. For a 100 W lamp operating in the vertical position, the temperature of the bulb surface is about 230 C at the top, 100 C at the center and 50 C at the base.

Advanced Topic:
Microscopic View of Incandescence

What is really happening at the microscopic level to cause the filament to glow when a voltage is applied across it? When a voltage is applied, the resultant electric field accelerates the free electrons in the tungsten metal. These electrons gain energy as they are accelerated. They then collide with the ions in the solid lattice and inelastically transfer some of their energy to the ions. Thus, the system of free electrons and ions cores, i.e. the tungsten wire, heats up. From energy conservation, this heat must be removed by some mechanism once the wire reaches an equilibrium temperature. This heat is removed by thermal conduction down the filament to the connecting wires and by the gas to the glass bulb and metal base, by thermal convection by the surrounding gas and by radiation. For a 100 W bulb, 82% of the heat energy is dissipated as radiation, 12% is dissipated by thermal convection of the gas and 6% is dissipated by thermal conduction. Most of the 82% of heat energy dissipated as radiation is in the infrared region (72%), while the rest is dissipated as predominantly visible light (10%), as shown in Fig. 2.

For a hot gas of say, hydrogen atoms, the radiation arises from colliding atoms of hydrogen that inelastically collide and knock their electrons into higher energy orbital shells. These electrons then fall back into an allowed lower energy orbital shell and emit light corresponding to the energy difference between the two orbital shells. In a solid, the situation is somewhat different. The discrete energy level of the electron orbital shell of an isolated atom is spread out into a continuum of very closely spaced energy levels when the free electron moves in the presence of a large numbers of atoms in a periodic array as there are in a solid, as shown in Fig. 3. Now, an energetic free electron (made energetic by its acceleration due to the applied voltage or by a collision with another energetic electron or by a collision with an energetically vibrating ion in the lattice) will lose its some of its energy by giving off radiation corresponding to the difference in energy between the electron's energy levels. In a solid, these energy levels are closely spaced, so that the radiation that is emitted is continuous, not discrete as it would be for an isolated atom. This is the origin of the blackbody radiation discussed earlier.

Advanced Topic:
A Brief History: The Edisonian Approach

Edison said, "When I want to discover something, I begin by reading up everything that has been done along that line in the past - that's what all these books in the library are for. I see what has been accomplished at great labor and expense in the past. I gather data of many thousands of experiments as a starting point, and then I make thousands more." This "Edisonian" approach to research and development is the basis for much of today's progress in science and technology.

Prior to Edison's work on the light bulb, most of the lamps had thick filaments with relatively low resistance and operated in a series circuit. These circuits operated at high currents and low voltages. Edison realized that in inventing an electric light usable for the masses, he had to consider the entire system, including lights, generators and transmission lines. This led him to the insight that the light bulbs must be arranged in parallel circuits so that lights could be individually turned on and off, much as gas jets could be turned on and off for the gas lighting that was common in the 1880's. He also came to realize that the light bulb must have a high resistance, use very little current and operate at a relatively high voltage. The low current bulb he invented greatly reduced the amount of (at the time) costly copper needed for the transmission lines (by a factor of about 100), compared to the low resistance bulbs proposed and being worked on by others.

Edison's most famous light bulb patent is attached as appendix 1.

This unit provides a natural tie-in to studies in economics and US history that involve the electrification of society, the industrial revolution, the rivalry between AC and DC distribution systems and the growth of industrial research laboratories.

Problems

1. Using $P=V^2/R$, calculate the hot resistance of the filament of a 60 W, 100 W and 200 W light bulb.

2. For these three bulbs, determine the current through each of the filaments when the light bulb is on.

3. The filament resistance when the light bulb is on is 15 times greater than its room temperature resistance. Determine the room temperature filament resistance of the three bulbs above.

4. The diameter of the filament of a 60 W, 100 W and 200 W bulb are 0.0046 cm, 0.0064 cm and 0.0102 cm respectively. Using the equation $R=\rho L/A$ and the fact that the room temperature resistivity of tungsten is 5.7×10^{-6} ohm-cm, determine the length of the filament of each of the three bulbs above.

5. Using the information determined above, calculate the temperature of the filament of each of these bulbs using the Stefan-Boltzmann law, assuming that the emissivity ε of tungsten is 0.3. Recall that the law is $P/S=\varepsilon\sigma T^4$, where S is the surface area of the filament, and the Stefan-Boltzmann constant σ is 5.67×10^{-12} W/(cm^2-K^4). Assume that the power dissipated in the filament as heat is all reemitted as radiation.

6. The lowest 2 wattages of a 3 way bulb are 25 W and 75 W. Determine the resistance of the filament when it is on at the highest wattage setting of the bulb.

7. Some people claim that if you are going to turn a lamp back on within one hour or so, then it is better to keep the lamp on (and not turn it off and then on again an hour later) because most of the energy is used when you first turn it on. Is this true? Is it more energy efficient to always turn off a light when you leave a room?

Solutions

1. a. $R = \frac{V^2}{P} = \frac{(120\ V)^2}{60\ W} = 240$ ohms

   b. $R = \frac{V^2}{P} = \frac{(120\ V)^2}{100\ W} = 144$ ohms

   c. $R = \frac{V^2}{P} = \frac{(120\ V)^2}{200\ W} = 72$ ohms

2. a. $I = \frac{V}{R} = \frac{120\ V}{240\ \text{ohms}} = 0.50$ Amps

   b. $I = \frac{V}{R} = \frac{120\ V}{144\ \text{ohms}} = 0.83$ Amps

   c. $I = \frac{V}{R} = \frac{120\ V}{72\ \text{ohms}} = 1.67$ Amps

3. a. $R_{\text{room temp.}} = \frac{240\ \text{ohms}}{15} = 16$ ohms

   b. $R_{\text{room temp.}} = \frac{144\ \text{ohms}}{15} = 9.6$ ohms

   c. $R_{\text{room temp.}} = \frac{72\ \text{ohms}}{15} = 4.8$ ohms

4. a. $L = \frac{RA}{\rho} = \frac{16\ \text{ohms} \times 3.14 \times (.0023\ \text{cm})^2}{5.7 \times 10^{-6}\ \text{ohm-cm}} = 47$ cm

   b. $L = \frac{RA}{\rho} = \frac{9.6\ \text{ohms} \times 3.14 \times (.0032\ \text{cm})^2}{5.7 \times 10^{-6}\ \text{ohm-cm}} = 54$ cm

   c. $L = \frac{RA}{\rho} = \frac{4.8\ \text{ohms} \times 3.14 \times (.0051\ \text{cm})^2}{5.7 \times 10^{-6}\ \text{ohm-cm}} = 69$ cm

5. a. $T^4 = \frac{P}{\varepsilon\sigma S}$

$= \frac{60 \text{ W}}{0.3 \times 5.67 \times 10^{-12} \text{ W-cm}^{-2}\text{-K}^{-4} \times 2 \times 3.14 \times .0023 \text{ cm} \times 47 \text{ cm}}$

T = 2685 K

b. $T^4 = \frac{P}{\varepsilon\sigma S}$

$= \frac{100 \text{ W}}{0.3 \times 5.67 \times 10^{-12} \text{ W-cm}^{-2}\text{-K}^{-4} \times 2 \times 3.14 \times .0032 \text{ cm} \times 54 \text{ cm}}$

T = 2713 K

c. $T^4 = \frac{P}{\varepsilon\sigma S}$

$= \frac{200 \text{ W}}{0.3 \times 5.67 \times 10^{-12} \text{ W-cm}^{-2}\text{-K}^{-4} \times 2 \times 3.14 \times .0051 \text{ cm} \times 69 \text{ cm}}$

T = 2701 K

6. *Solution 1*

For the 25 W bulb, the hot resistance is:

$$R = \frac{V^2}{P} = \frac{(120\ V)^2}{25\ W} = 576 \text{ ohms.}$$

For the 75 W bulb, the hot resistance is:

$$R = \frac{V^2}{P} = \frac{(120\ V)^2}{75\ W} = 192 \text{ ohms.}$$

The hot resistance at the highest setting of the bulb corresponds to the parallel combination of the 25 W and 75 W filaments, so

$$R = \frac{576 \text{ ohms} \times 192 \text{ ohms}}{(576 \text{ ohms} + 192 \text{ ohms})} = 144 \text{ ohms.}$$

Solution 2

The wattage at the highest setting is the sum of the two lower wattages or 100 W.

Therefore, $R = \frac{V^2}{P} = \frac{(120\ V)^2}{100W} = 144$ ohms.

7. It is always better to turn off the lights whenever you leave the room.

The power used by the lamp when it is just turned on is almost 15 times greater than the power used when it is hot, as we learned in experiments 1 and 2.

(Recall that $P=V^2/R$, V is 120 V when the lamp is on and 0 V when the lamp is off, and $R_{hot\ filament} = 15\ R_{cold\ filament}$ so that $P_{cold} = 15P_{hot}$)

The energy used in a given time period t is given by the E = P x t where P is the power. After the lamp is turned on, the time the filament is cold is very short, certainly less than 1 second, because the lamp is instantly bright - it does not slowly build up in brightness. So the power dissipated when the filament is cold (but heating up) during the first second is at most 15 times greater than the power dissipated when the filament is hot for 1 second. Therefore it is more energy efficient to turn off a lamp unless you plan on turning it on again within 15 seconds or so.

An example is shown on the next page. The first light bulb is turned on for 15 sec, then turned off for 45 sec, then turned on again for 10 sec. The second bulb is turned on and kept on for the next 70 sec.

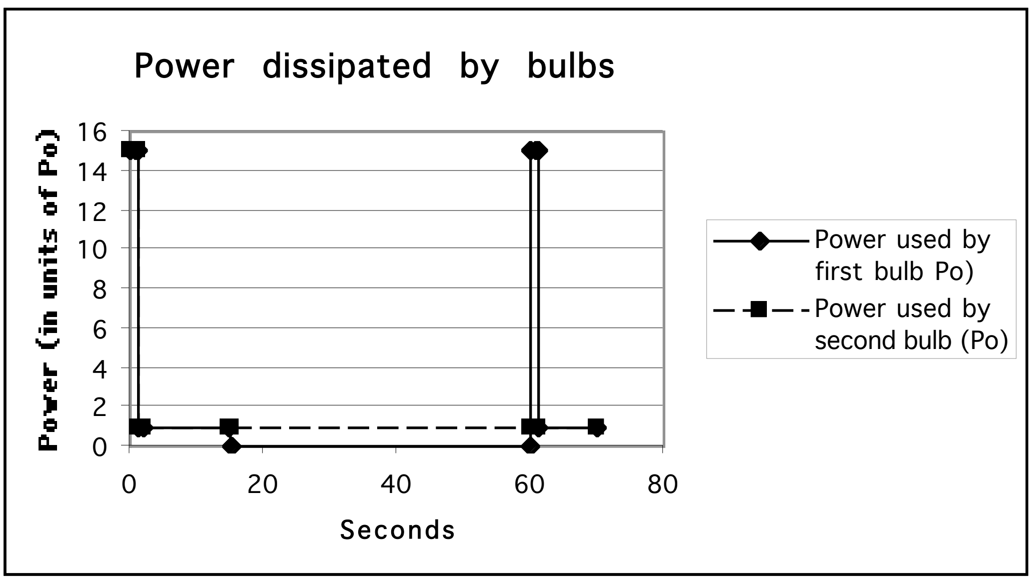
Recall E = P x t and assume that the power dissipated when the bulb is cold (but heating up) is $15P_0$ and that the power dissipated when the bulb is hot is P_0.

The energy used by the first bulb is:
$E = 15\ P_0 \times 1\ \text{sec} + P_0 \times 14\ \text{sec} + 0 \times 45\ \text{sec} + 15\ P_0 \times 1\ \text{sec} + P_0 \times 9\ \text{sec} = 53\ P_0 - \text{sec}$

The energy used by the second bulb is:
$E = 15\ P_0 \times 1\ \text{sec} + P_0 \times 69\ \text{sec} = 84\ P_0 - \text{sec}$

So the second bulb used less energy than the first bulb.

Time (sec)	Power used by first bulb (units of P_0)	Power used by second bulb (units of P_0)
0	15	15
0.9	15	15
1	15	15
1.1	1	1
2	1	1
14.9	1	1
15	0	1
15	0	1
59.9	0	1
60	15	1
60.9	15	1
61	15	1
61.1	1	1
70	1	1
70	1	1



References

1. "Illuminating Physics with Light Bulbs," Harvey S. Leff, *The Physics Teacher*, January 1990, pp. 30-35.

2. "Basic Physics of the Incandescent Lamp (Lightbulb), D. MacIsaac, G. Kanner, and G. Anderson, *The Physics Teacher* **37**, December 1999, pp. 520-525.

3. "Efficiency and efficacy of incandescent lamps," D. C. Agrawal, H. S. Leff, and V. J. Menon, *American Journal of Physics* **64**, 649-654 (1966).

4. "The Coolidge Process for Making Tungsten Ductile: The Foundation of Incandescent Lighting," C. L. Briant and B. P. Bewlay, *Materials Research Bulletin*, August 1995, pp. 67-73.

5. "The electric lamp: 100 years of applied physics," John M. Anderson and John S. Saby, *Physics Today*, October 1979, pp. 32-40.

6. "Incandescent Lamps," General Electric publication TP-110R2, May 1984.

7. Lamps and Lighting, edited by H. Hewitt and A. S. Vause, American Elsevier Publishing Co., New York 1966.

8. "The Extraordinary Light Bulb … Its parts and assembly," General Electric Lamp Division publication 112-9182.

Materials Required

Experiment 1:

1.Ohmmeter - digital autoranging preferred such as the VWRbrand Digital Autorange Multimeter P/N 26983-175. Call VWR at 800-932-5000. List price: $29.95. Ohmmeters/Multimeters are also available at Radio Shack.
2. 100 W light bulb.
3. Other wattage light bulbs.

Experiment 2:

1. Ohmmeter.
2. 100 W light bulb.

Experiment 3:

1. Ohmmeter.
2. 50 W - 100 W - 150 W   3 way light bulb.
3. 3 way switch socket available at Home Depot and most other hardware stores.

Experiment 4:

No special materials are necessary

Experiment 5:

1. Light bulb 100 W or 50 W - 100 W - 150 W 3 way bulb
2. Hammer
3. Newspaper
4. Safety goggles
5. Gloves

Experiment 6:

1. Variac transformer or power supply or voltage source with 100 V capability.
2. Copper wires - standard hook up wire available at hardware stores or Radio Shack.
3. 0.010 inch diameter Kanthal AF, Kanthal A1 or Hoskins 875 heater wire - available from California Fine Wire Company 805-4895144. Nichrome heater wire will also work.

4. 0.003 inch diameter Kanthal AF, Kanthal A1 or Hoskins 875 heater wire - available from California Fine Wire Company 805-4895144. Nichrome heater wire will also work.

A kit containing items 2, 3, and 4 is available through the GA Sciences Education Foundation as item GASEF # 013. Go to
www.sci-ed-ga.org/modules/materialscience/color/materials.html
for details about the kit and
www.sci-ed-ga.org/modules/materialscience/color/orderform.html
for ordering information.

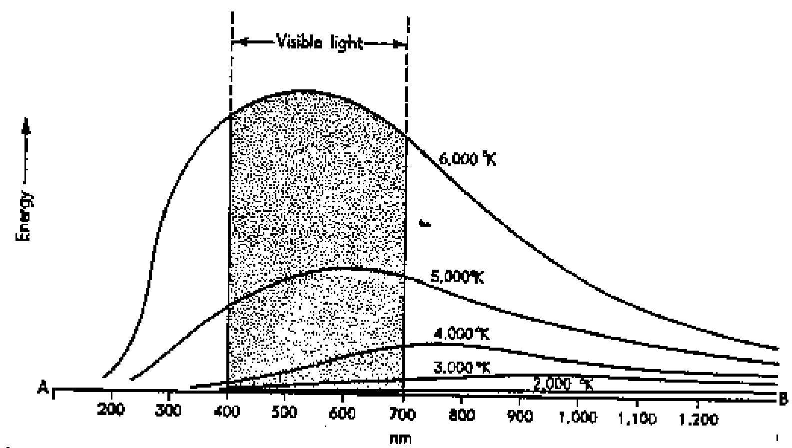


Fig. 1 Spectral power distribution of black body at various temperatures

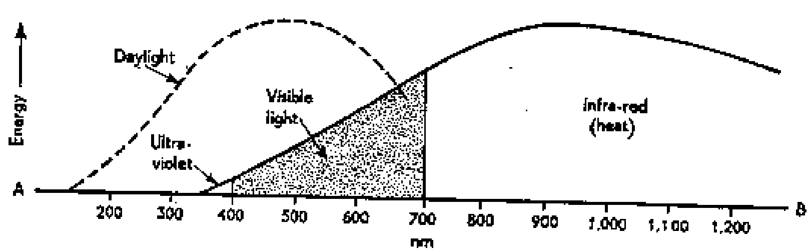
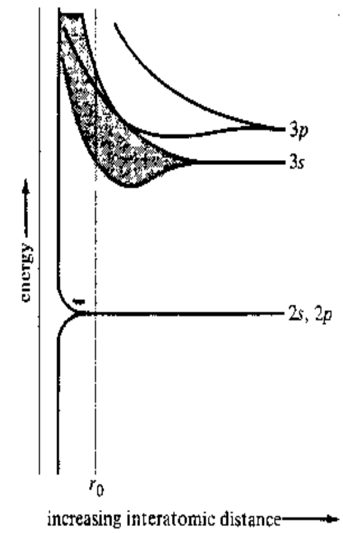


Fig. 2 Spectral power distribution of a gas-filled incandescent lamp



Energy Bands in Magnesium

At the interatomic distance, r_0, in the magnesium crystal, the filled 3s band overlaps the empty band of 3p orbitals, permitting easy promotion of an electron.

Energy Bands in an Insulator

At the interatomic distance. r_0, there is a large gap between the band of valence shell orbitals and the next higher band of orbitals. However, at smaller distances, r', the filled and empty bands overlap.

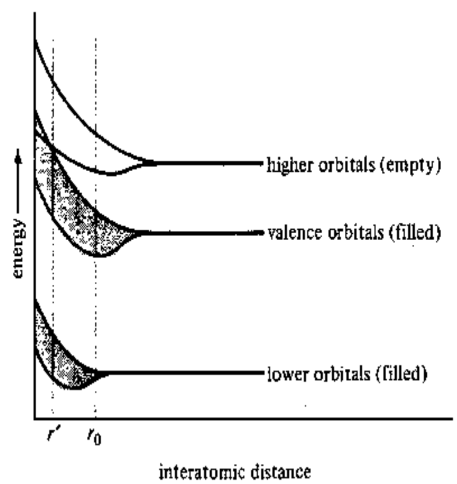


Fig. 3 Energy Bands in a Metal (ABOVE) AND AN INSULATOR (BELOW).

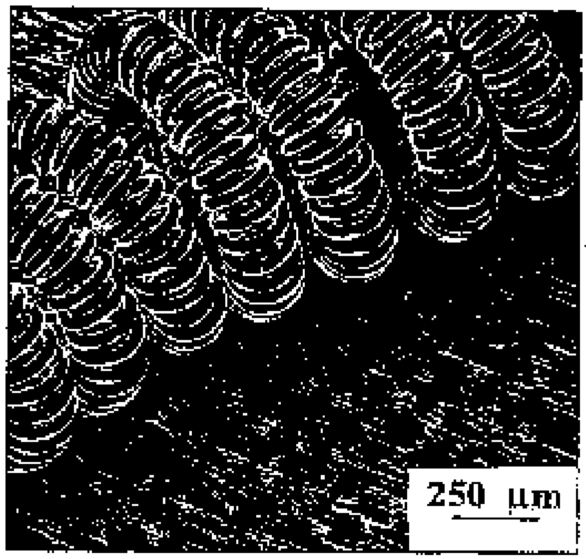
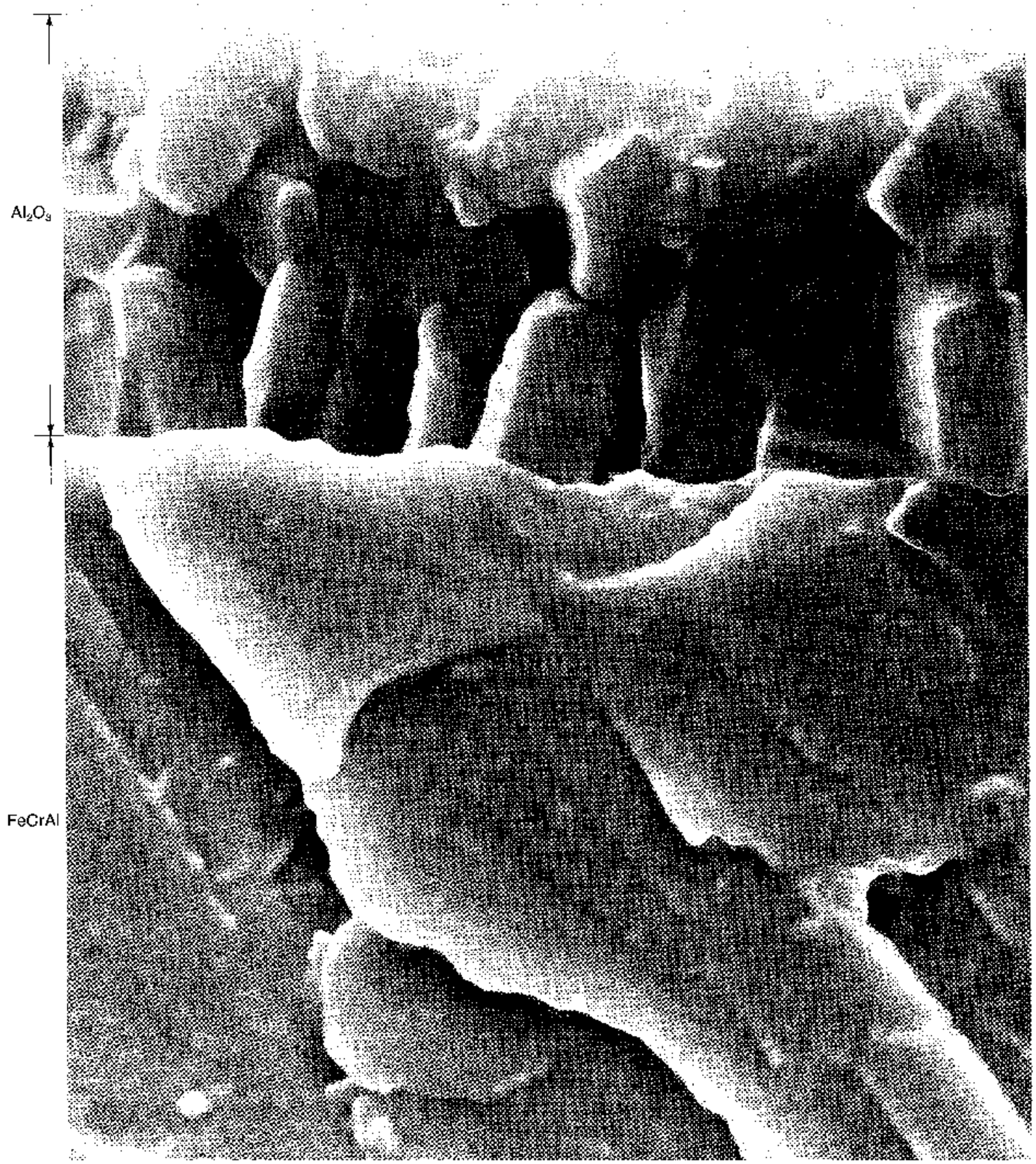


Figure #4 An example of a coiled-coil filament used in most incandescent lamps today. This figure shows an SEM micrograph of a section of filament that has been removed from the lamp.

Figure-5

Cross Section of KANTHAL Wire X 3000



UNITED STATES PATENT OFFICE.

THOMAS A. EDISON, OF MENLO PARK, NEW JERSEY.

ELECTRIC LAMP.

SPECIFICATION forming part of Letters Patent No. 223,898, dated January 27, 1880.

Application filed November 4, 1879.

To all whom it may concern:

Be it known that I, THOMAS ALVA EDISON, of Menlo Park, in the State of New Jersey, United States of America, have invented an Improvement in Electric Lamps, and in the method of manufacturing the same, (Case No. 186,) of which the following is a specification.

The object of this invention is to produce electric lamps giving light by incandescence, which lamps shall have high resistance, so as to allow of the practical subdivision of the electric light.

The invention consists in a light-giving body of carbon wire or sheets coiled or arranged in such a manner as to offer great resistance to the passage of the electric current, and at the same time present but a slight surface from which radiation can take place.

The invention further consists in placing such burner of great resistance in a nearly-perfect vacuum, to prevent oxidation and injury to the conductor by the atmosphere. The current is conducted into the vacuum-bulb through platina wires sealed into the glass.

The invention further consists in the method of manufacturing carbon conductors of high resistance, so as to be suitable for giving light by incandescence, and in the manner of securing perfect contact between the metallic conductors or leading-wires and the carbon conductor.

Heretofore light by incandescence has been obtained from rods of carbon of one to four ohms resistance, placed in closed vessels, in which the atmospheric air has been replaced by gases that do not combine chemically with the carbon. The vessel holding the burner has been composed of glass cemented to a metallic base. The connection between the leading-wires and the carbon has been obtained by clamping the carbon to the metal. The leading-wires have always been large, so that their resistance shall be many times less than the burner, and, in general, the attempts of previous persons have been to reduce the resistance of the carbon rod. The disadvantages of following this practice are, that a lamp having but one to four ohms resistance cannot be worked in great numbers in multiple arc without the employment of main conductors of enormous dimensions; that, owing to the low resistance of the lamp, the leading-wires must be of large dimensions and good conductors, and a glass globe cannot be kept tight at the place where the wires pass in and are cemented; hence the carbon is consumed, because there must be almost a perfect vacuum to render the carbon stable, especially when such carbon is small in mass and high in electrical resistance.

The use of a gas in the receiver at the atmospheric pressure, although not attacking the carbon, serves to destroy it in time by "air-washing," or the attrition produced by the rapid passage of the air over the slightly-coherent highly-heated surface of the carbon. I have reversed this practice. I have discovered that even a cotton thread properly carbonized and placed in a sealed glass bulb exhausted to one-millionth of an atmosphere offers from one hundred to five hundred ohms resistance to the passage of the current, and that it is absolutely stable at very high temperatures; that if the thread be coiled as a spiral and carbonized, or if any fibrous vegetable substance which will leave a carbon residue after heating in a closed chamber be so coiled, as much as two thousand ohms resistance may be obtained without presenting a radiating-surface greater than three-sixteenths of an inch; that if such fibrous material be rubbed with a plastic composed of lamp-black and tar, its resistance may be made high or low, according to the amount of lamp-black placed upon it; that carbon filaments may be made by a combination of tar and lamp-black, the latter being previously ignited in a closed crucible for several hours and afterward moistened and kneaded until it assumes the consistency of thick putty. Small pieces of this material may be rolled out in the form of wire as small as seven-one-thousandths of an inch in diameter and over a foot in length, and the same may be coated with a non-conducting non-carbonizing substance and wound on a bobbin, or as a spiral, and the tar carbonized in a closed chamber by subjecting it to high heat, the spiral after carbonization retaining its form.

All these forms are fragile and cannot be clamped to the leading-wires with sufficient force to insure good contact and prevent heating. I have discovered that if platinum wires are used and the plastic lamp-black and tar

APPENDIX 1.

material be molded around it in the act of carbonization there is an intimate union by combination and by pressure between the carbon and platina, and nearly perfect contact is obtained without the necessity of clamps; hence the burner and the leading-wires are connected to the carbon ready to be placed in the vacuum-bulb.

When fibrous material is used the plastic lamp-black and tar are used to secure it to the platina before carbonizing.

By using the carbon wire of such high resistance I am enabled to use fine platinum wires for leading-wires, as they will have a small resistance compared to the burner, and hence will not heat and crack the sealed vacuum-bulb. Platina can only be used, as its expansion is nearly the same as that of glass.

By using a considerable length of carbon wire and coiling it the exterior, which is only a small portion of its entire surface, will form the principal radiating-surface; hence I am able to raise the specific heat of the whole of the carbon, and thus prevent the rapid reception and disappearance of the light, which on a plain wire is prejudicial, as it shows the least unsteadiness of the current by the flickering of the light; but if the current is steady the defect does not show.

I have carbonized and used cotton and linen thread, wood splints, papers coiled in various ways, also lamp-black, plumbago, and carbon in various forms, mixed with tar and kneaded so that the same may be rolled out into wires of various lengths and diameters. Each wire, however, is to be uniform in size throughout.

If the carbon thread is liable to be distorted during carbonization it is to be coiled between a helix of copper wire. The ends of the carbon or filament are secured to the platina leading-wires by plastic carbonizable material, and the whole placed in the carbonizing-chamber. The copper, which has served to prevent distortion of the carbon thread, is afterward eaten away by nitric acid, and the spiral soaked in water, and then dried and placed on the glass holder, and a glass bulb blown over the whole, with a leading-tube for exhaustion by a mercury-pump. This tube, when a high vacuum has been reached, is hermetically sealed.

With substances which are not greatly distorted in carbonizing, they may be coated with a non-conducting non-carbonizable substance, which allows one coil or turn of the carbon to rest upon and be supported by the other.

In the drawings, Figure 1 shows the lamp sectionally. *a* is the carbon spiral or thread. *c c'* are the thickened ends of the spiral, formed of the plastic compound of lamp-black and tar. *d d'* are the platina wires. *h h* are the clamps, which serve to connect the platina wires, cemented in the carbon, with the leading-wires *x x*, sealed in the glass vacuum-bulb. *e e* are copper wires, connected just outside the bulb to the wires *x x*. *m* is the tube (shown by dotted lines) leading to the vacuum-pump, which, after exhaustion, is hermetically sealed and the surplus removed.

Fig. 2 represents the plastic material before being wound into a spiral.

Fig. 3 shows the spiral after carbonization, ready to have a bulb blown over it.

I claim as my invention—

1. An electric lamp for giving light by incandescence, consisting of a filament of carbon of high resistance, made as described, and secured to metallic wires, as set forth.

2. The combination of carbon filaments with a receiver made entirely of glass and conductors passing through the glass, and from which receiver the air is exhausted, for the purposes set forth.

3. A carbon filament or strip coiled and connected to electric conductors so that only a portion of the surface of such carbon conductors shall be exposed for radiating light, as set forth.

4. The method herein described of securing the platina contact-wires to the carbon filament and carbonizing of the whole in a closed chamber, substantially as set forth.

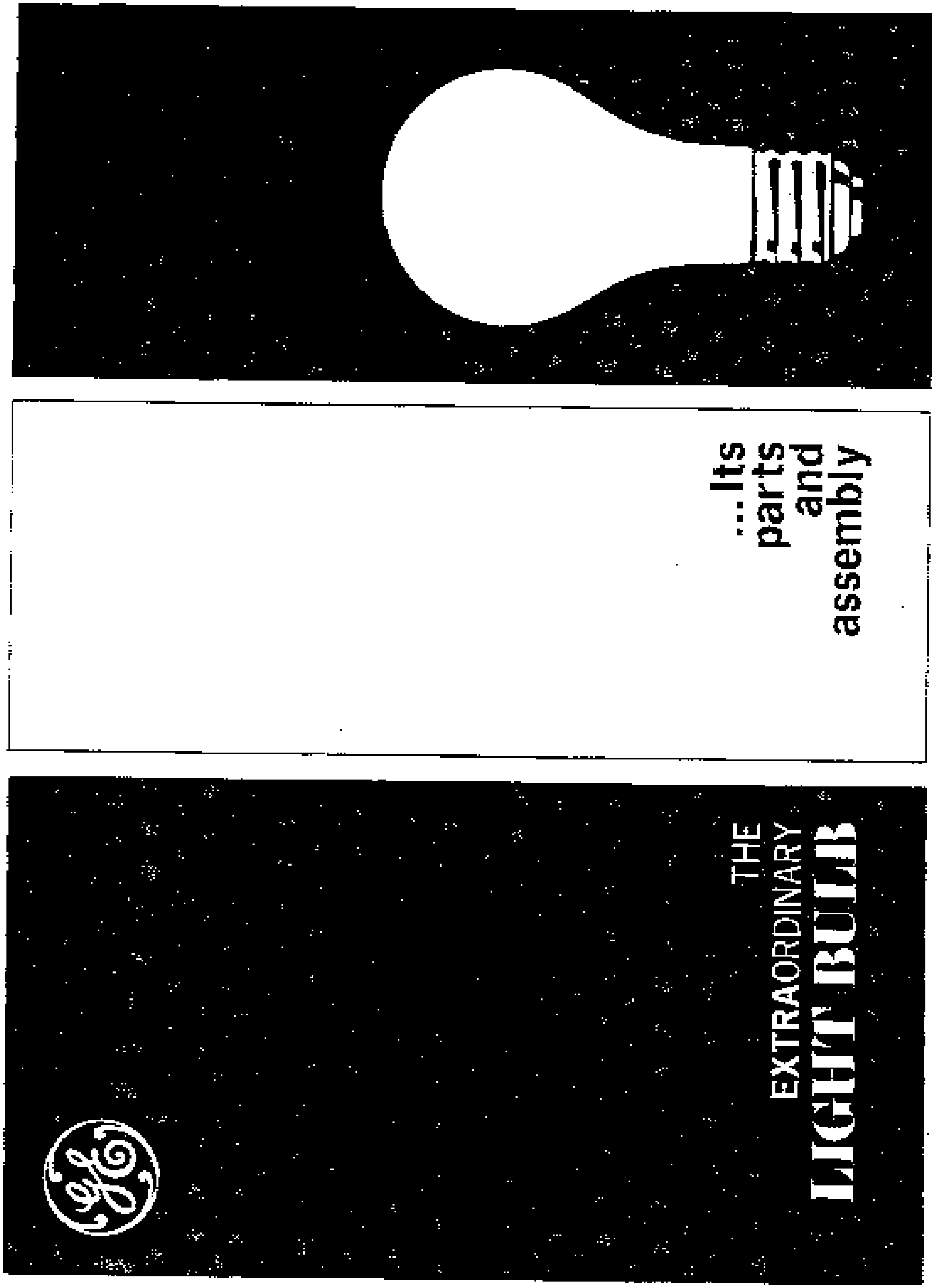
Signed by me this 1st day of November, A. D. 1879.

THOMAS A. EDISON.

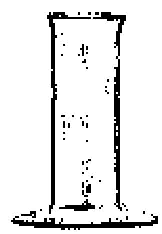
Witnesses:

S. L. GRIFFIN,
JOHN F. RANDOLPH.

Appendix 2

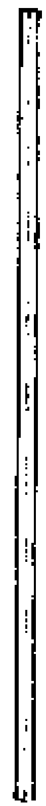


Technically, a light bulb is called a lamp. A lamp is assembled from ten basic parts:

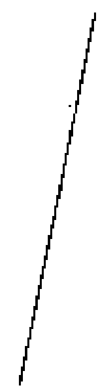


flare;

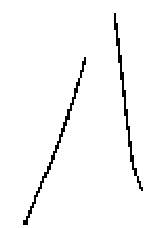
two lead wires, which look almost alike;



exhaust tubing;

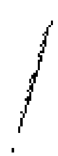


one support wire;

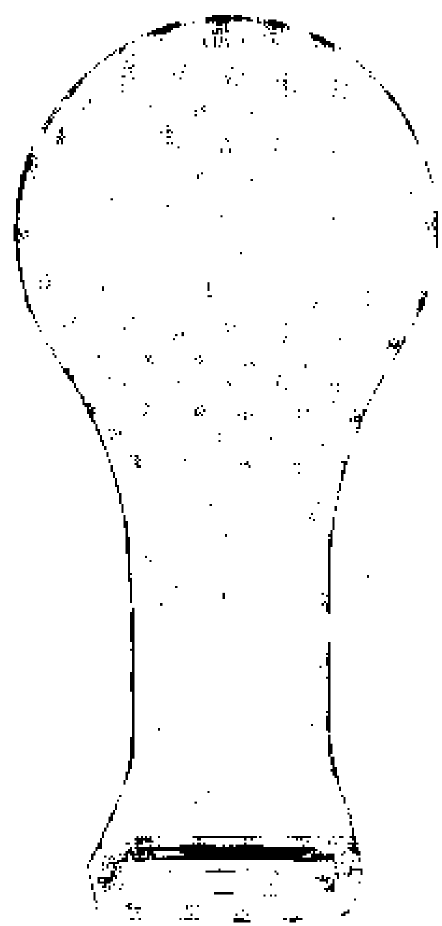


two anchor wires, which look almost alike;

2



filament;

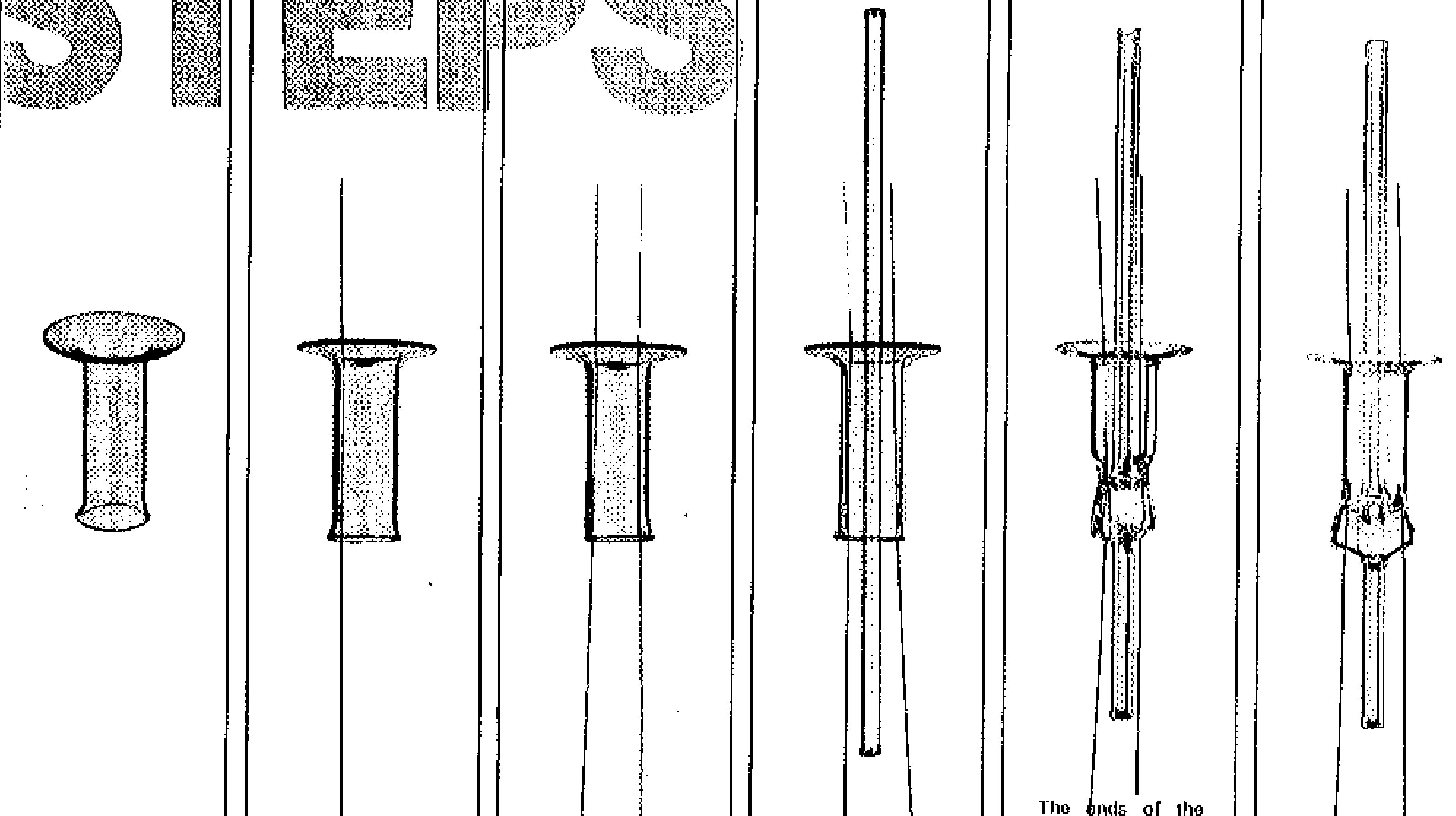


bulb;

and base.

Though these parts are shaped and assembled entirely by machines, in order to give you a good look at the assembly process we will put one together "by hand."

STEPS



At the first step of the process, we have only the flare.

Next, one of the lead wires is placed through the flare.

The second lead wire is then placed opposite the first inside the flare.

The exhaust tube is placed through the flare between the lead wires.

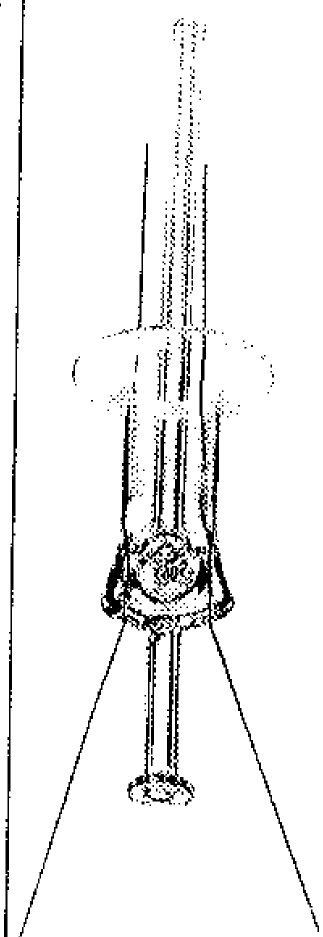
The ends of the flare and exhaust tube are heated and pressed together so that the flare, the exhaust tube, and the two lead wires now form one unit.

A small hole is blown through the flare just above the point where the parts were pressed together.

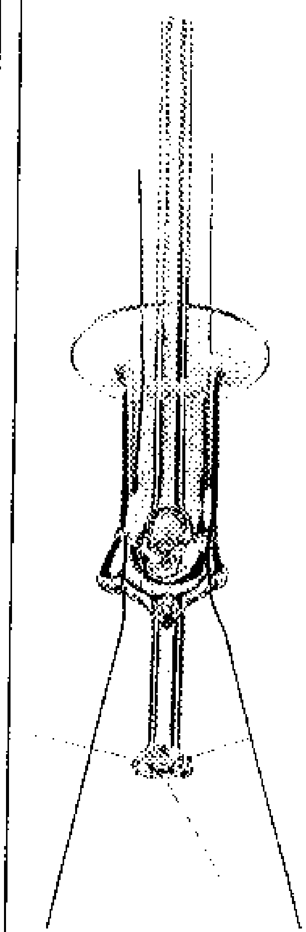
4

This completes the stage of the assembly which is called the "stem".

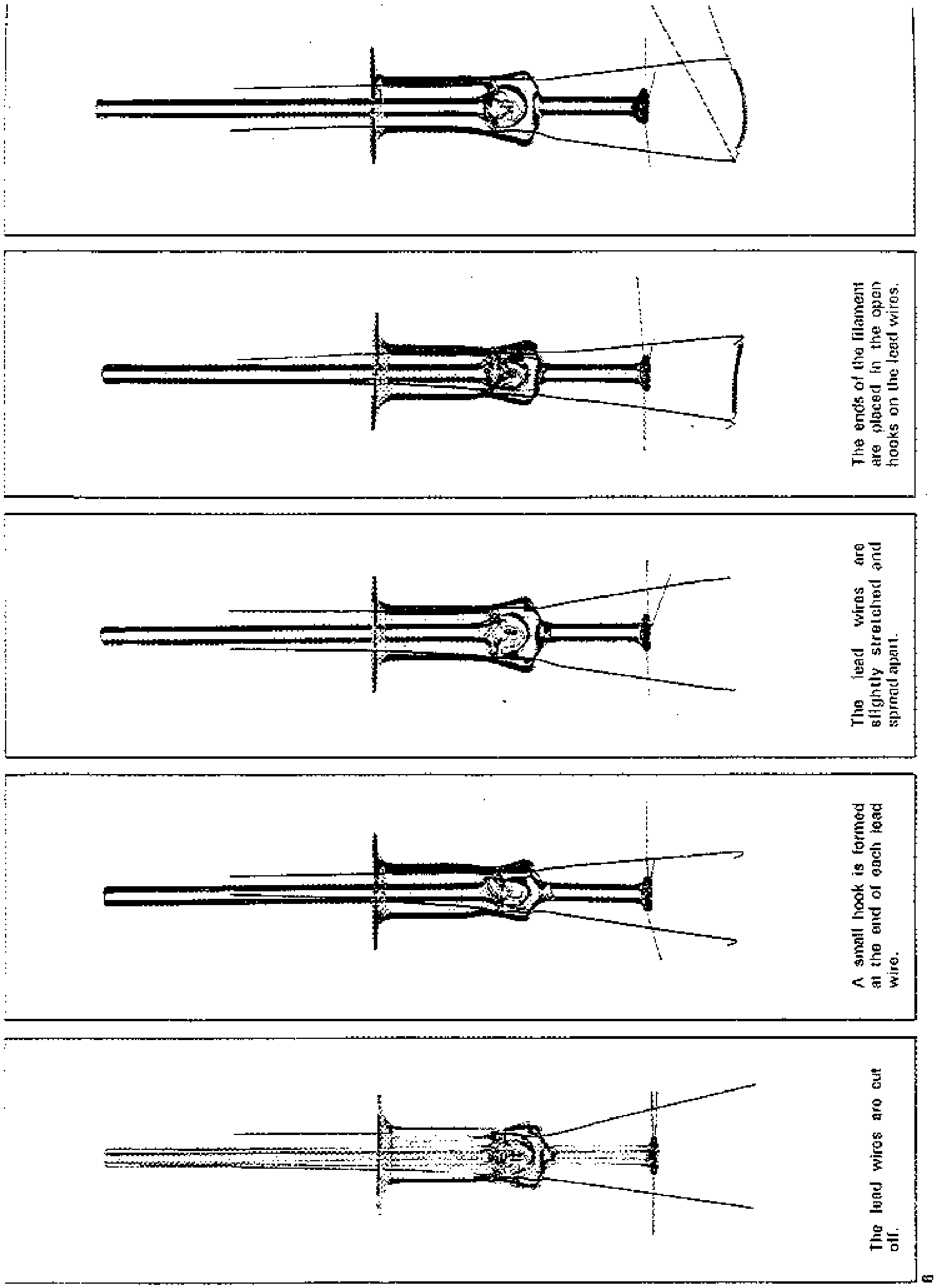
Next . . .

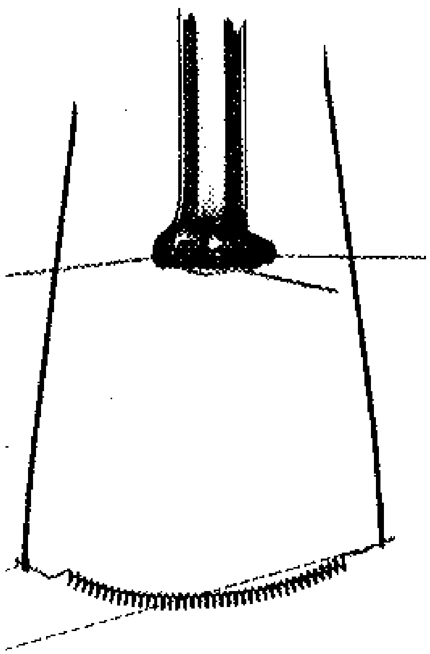


The bottom end of the exhaust tube is heated and formed into a "button".

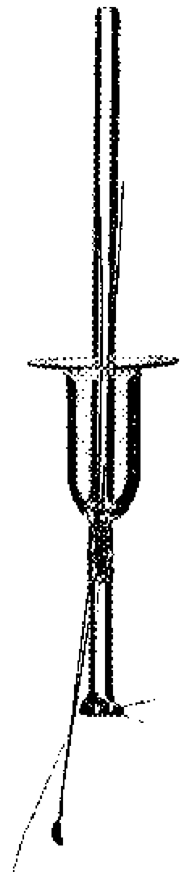


At the same time as step B, the support wire and the two anchor wires are forced into the heated button.

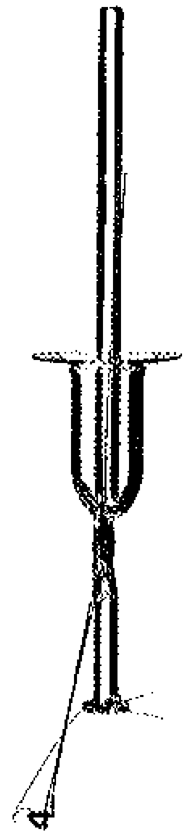

The lead wires are cut off.
A small hook is formed at the end of each lead wire.
The lead wires are slightly stretched and spread apart.
The ends of the filament are placed in the open hooks on the lead wires.
6



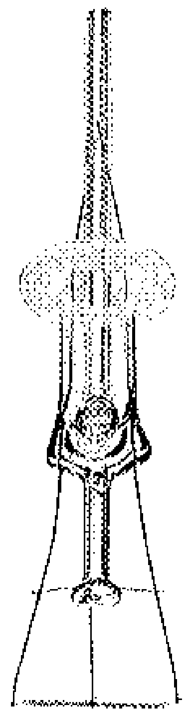
These hooks are closed.



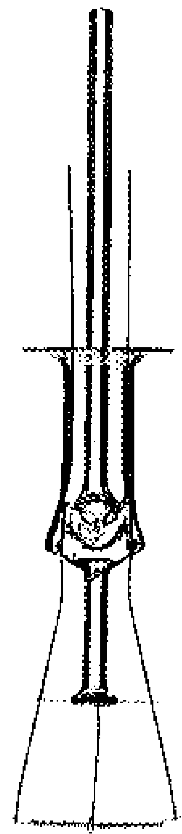
While these hooks are being closed, the support wire is bent down toward the filament.



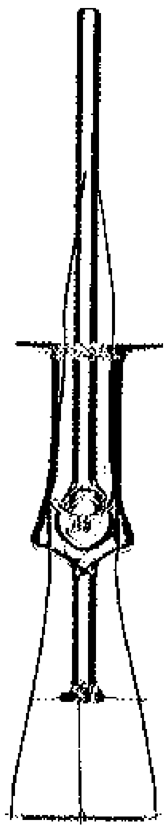
The end of the support wire is formed in a loop around the filament.



The ends of the anchor wires are formed in loops around the lead wires.

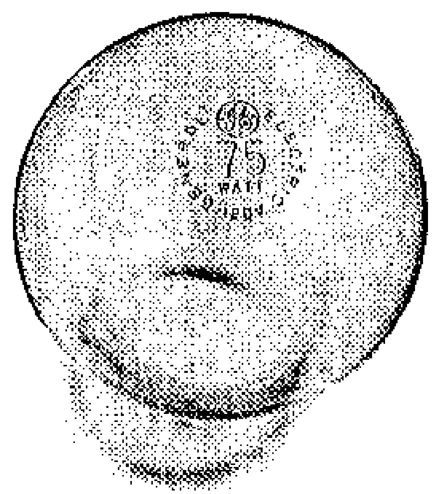


The lead wires are bent inward above the anchor wires, so that the ends of the lead wires are properly spaced.

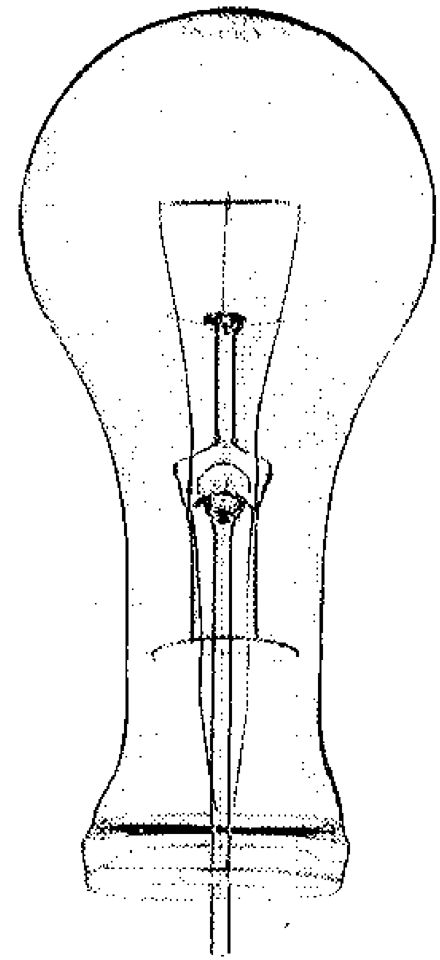


The upper ends of the lead wires are bent inward.

The filament is now dipped into a solution. This completes the inner assembly of the lamp, which is called the "mount".

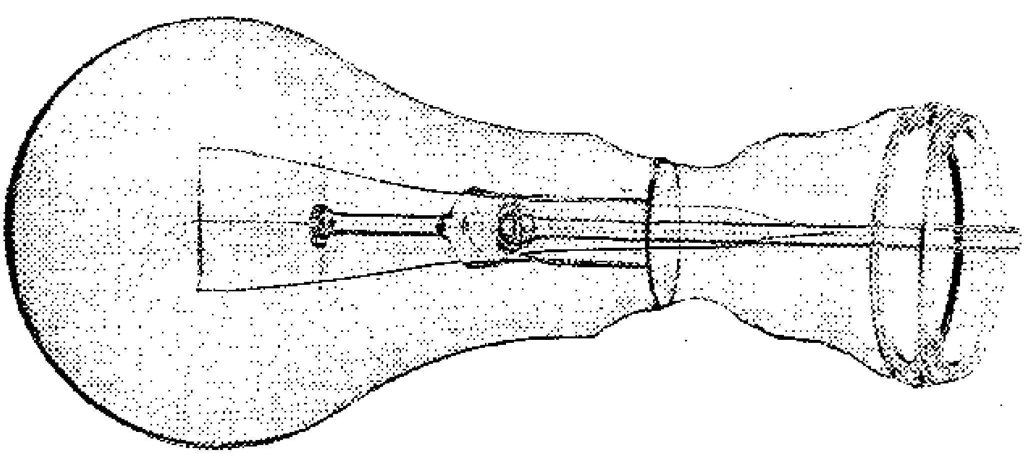


The bulb is marked with the lamp size and the GE monogram.

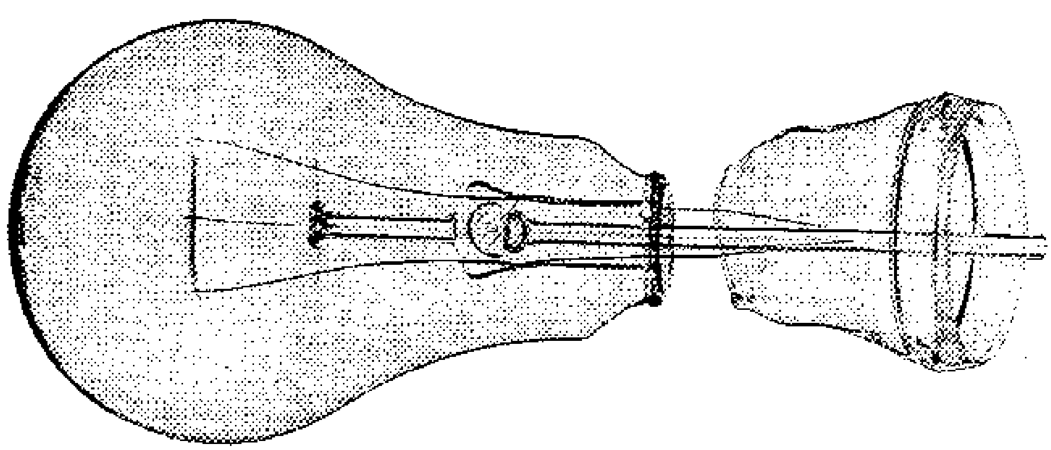


The bulb is placed over the mount. Notice that the mount has been turned over.

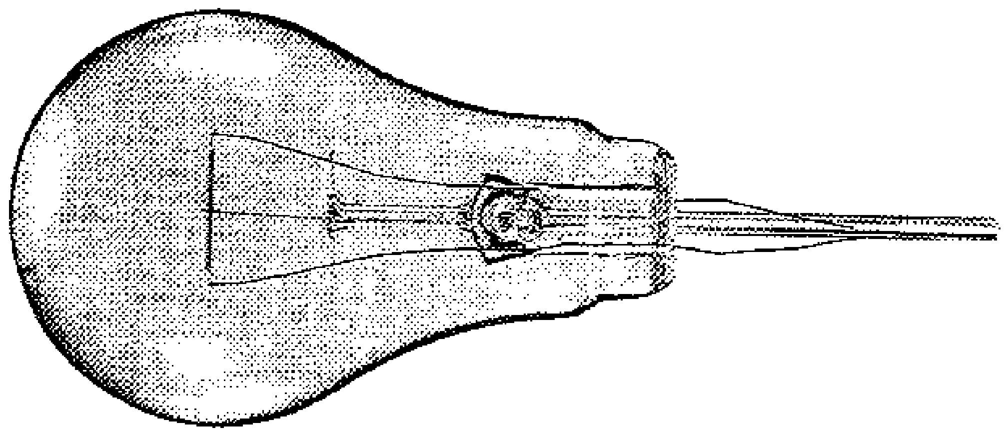
8



The neck of the bulb and the bottom of the flare are heated and joined.

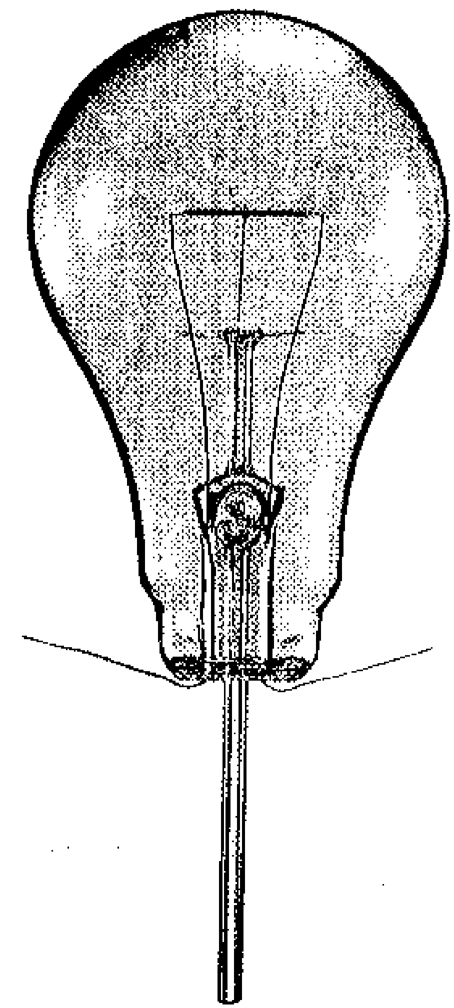


The part of the bulb below this joint is heated and cut off.

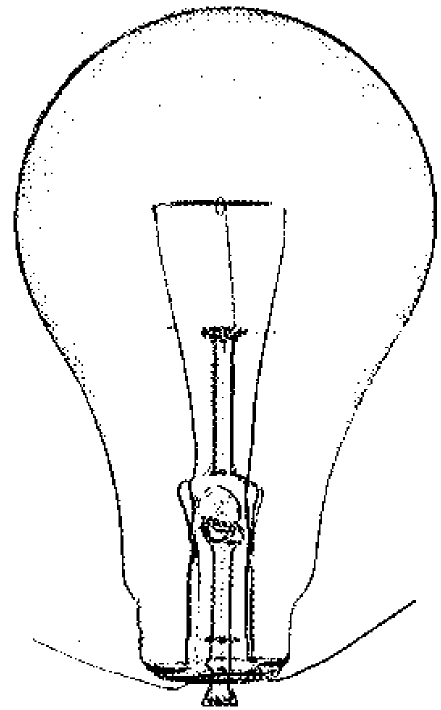


The bottom of this assembly is molded, while under heat, to fit the base.

The air is now removed through the ex-haust tube, and the bulb is flushed out with a gas. Another gas is then forced into the bulb.

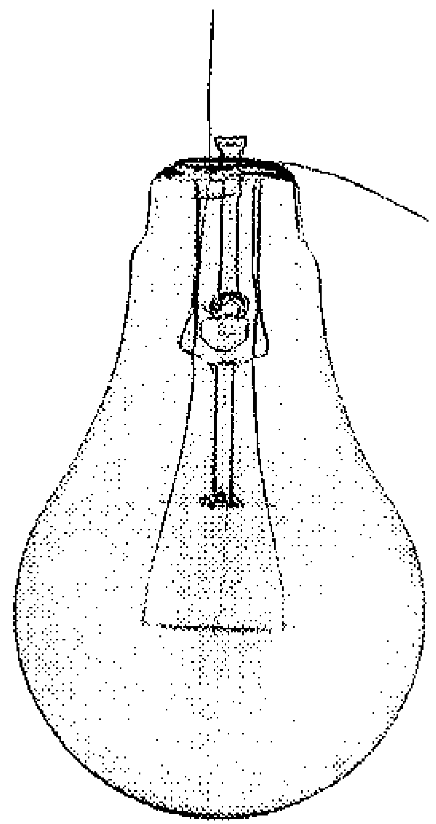


During this flushing stage, the outer ends of the lead wires are bent straight out.

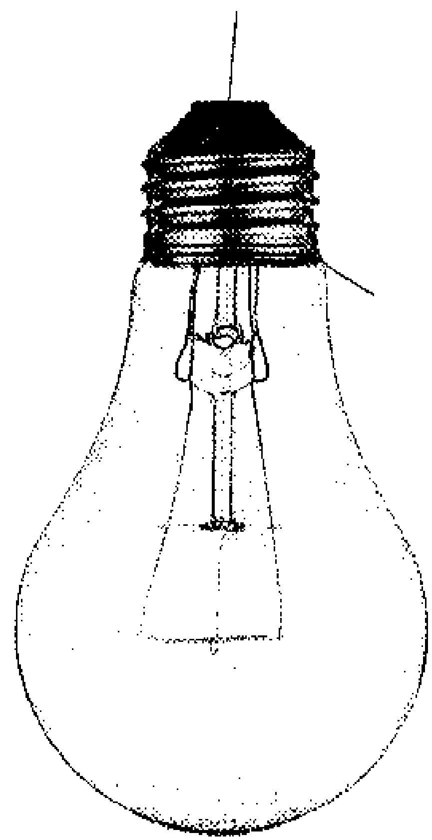


The tip of the exhaust tube is heated and cut off.

At this point, the assembly is called an "unbased lamp." It could actually be lighted.

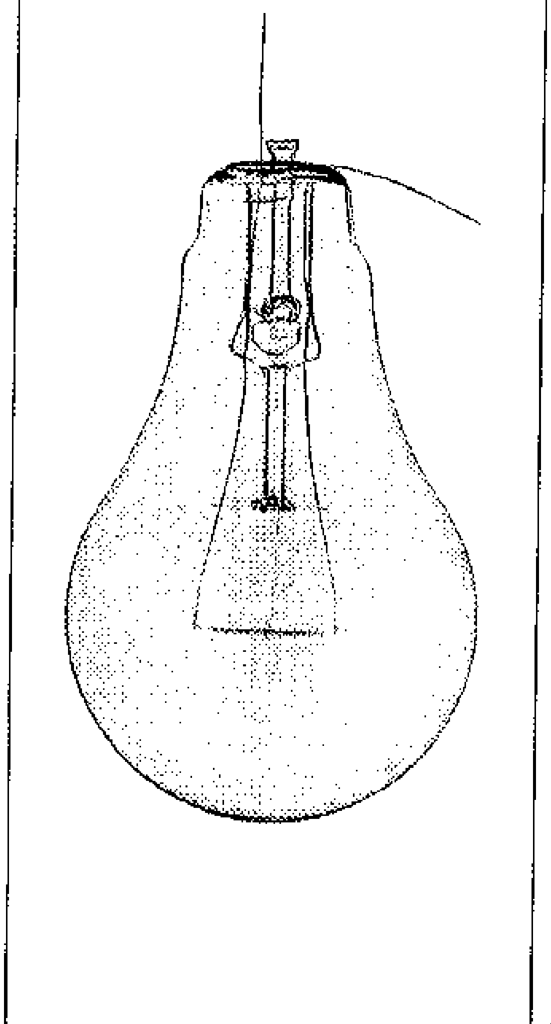


One of the lead wires is bent again so that it is straight up and down. Notice that the lamp has been turned over again.

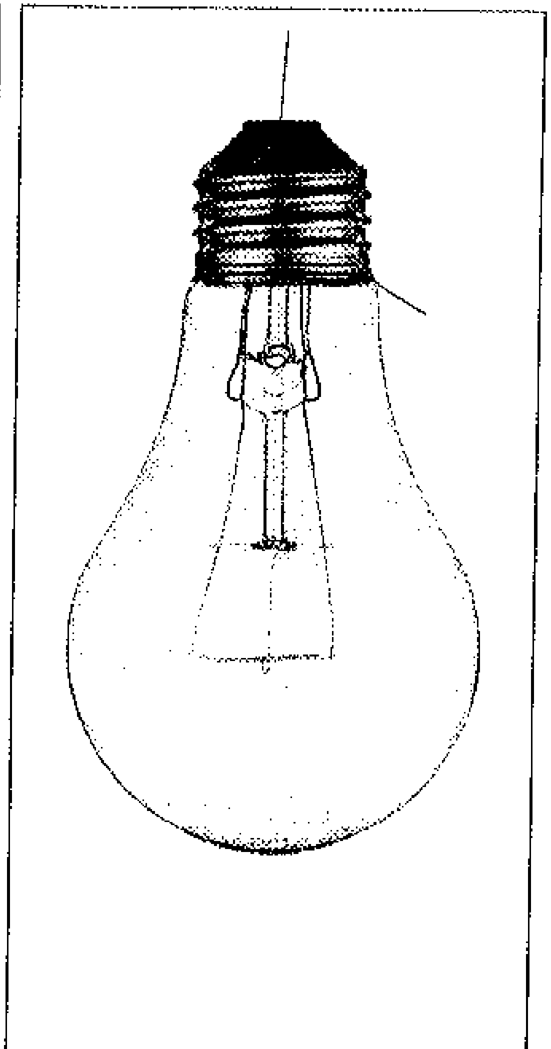


The base is placed on the lamp.

The base is now baked on and a kind of oil is applied to the threads of the base.

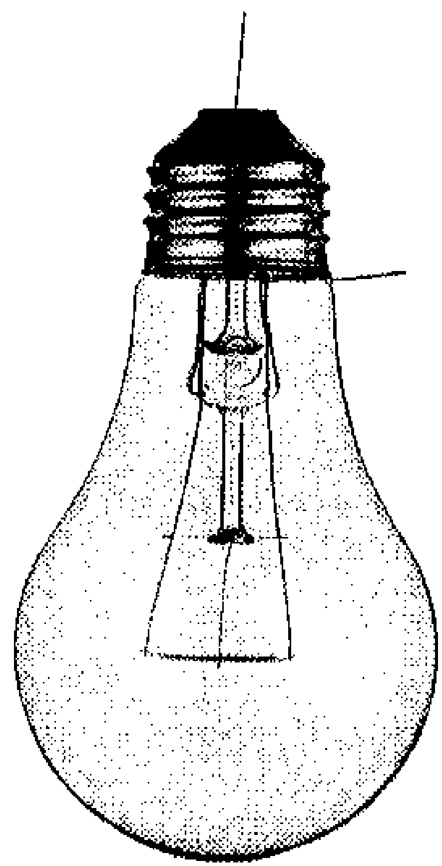


One of the lead wires is bent again so that it is straight up and down. Notice that the lamp has been turned over again.

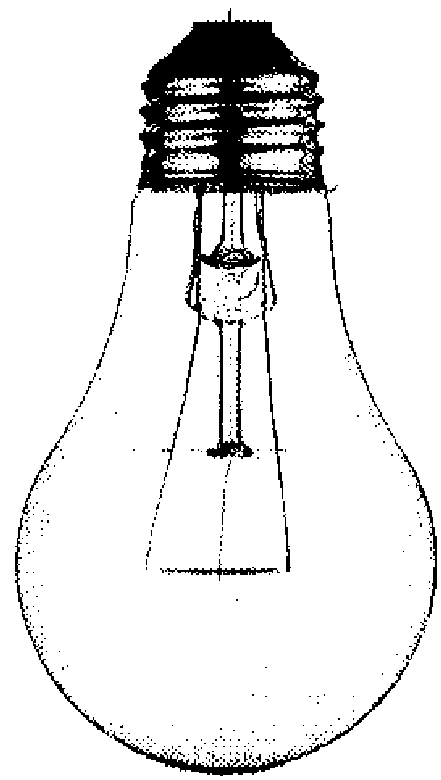


The base is placed on the lamp.

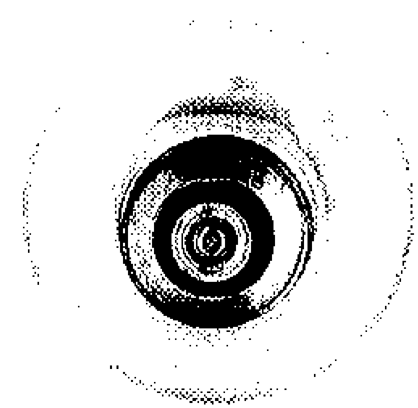
The base is now baked on and a kind of oil is applied to the threads of the base.



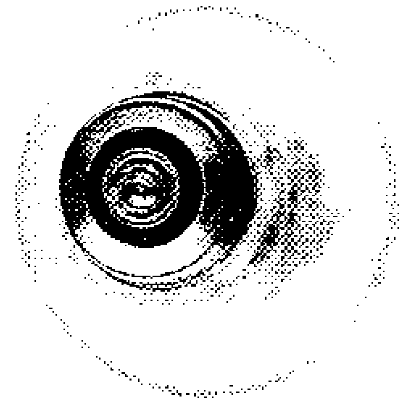
One lead wire is bent straight out and the other straight up.



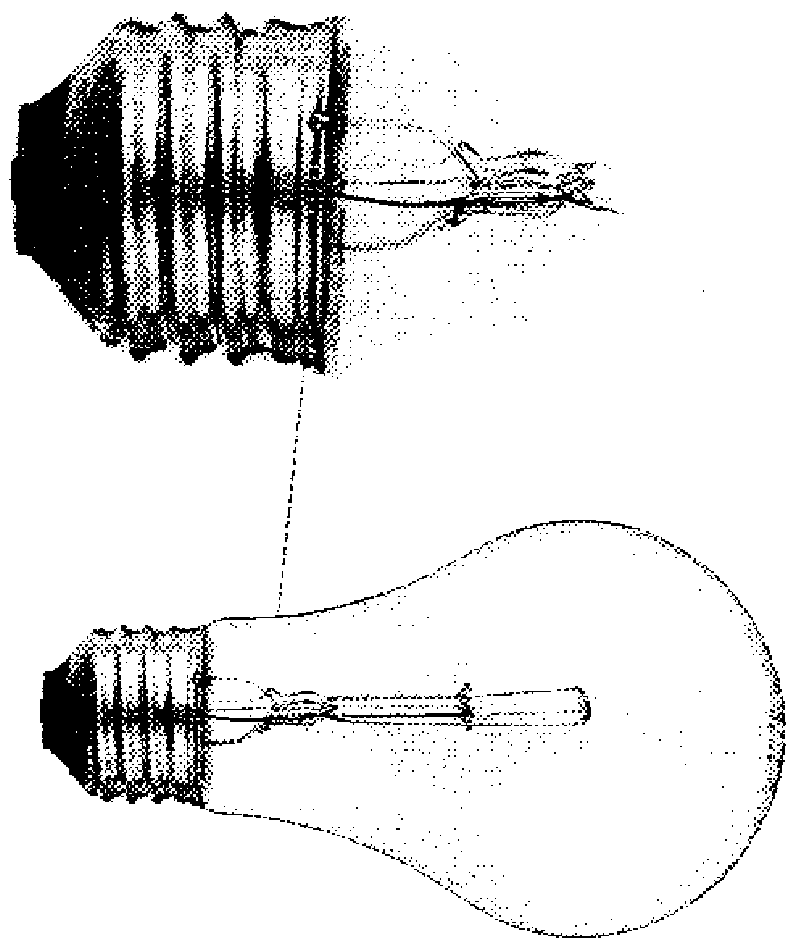
The ends of the lead wires are cut off.



The lead wire passing through the end of the base is flattened and a drop of "flux" is put on the end of the base.

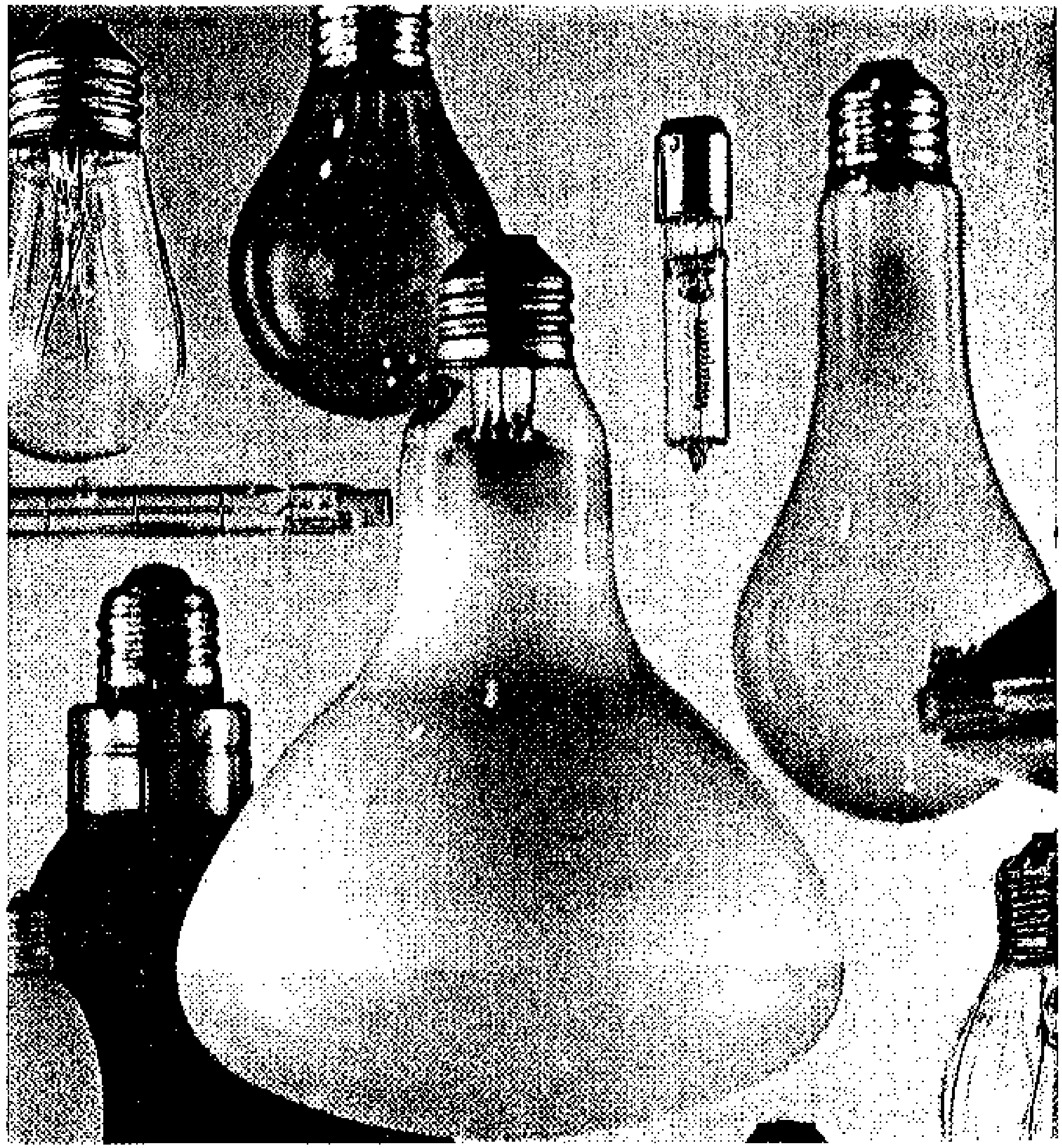


The end of the lead wire passing through the end of the base is soldered.



The end of the lead wire on the side is welded to the base.

The filament is now "aged" by lighting the lamp. The lamp is then tested for quality. This completes the assembly of the lamp.



THE LIGHT BULB:

PRECISION INSTRUMENT

Today's incandescent light bulb has little in common with Edison's 1879 light. It comes in hundreds of sizes, shapes, finishes, colors, with a wide variety of electrical and performance characteristics. It has countless applications.

Take just one — the popular 100-watt household bulb. About 300 million are made in this country each year. In such numbers what could be more commonplace than a bulb of glass, metal and gas? But if the bulb is commonplace, it is far from ordinary.

The glass used in bulbs is especially designed to transmit maximum light, strong enough to withstand temperatures varying from below zero to 850 degrees, rugged enough to withstand rough handling.

To assure these characteristics, General Electric produces its own bulbs from a special, chemically pure sand, joined with soda ash and limestone in furnaces at 2050° Fahrenheit.

HEART OF A LIGHT BULB

The most critical part of a light bulb is its filament. This part glows white-hot and produces light when electricity passes through it. The filament is tungsten, with a higher melting point than any other metal. It's a rarer metal than gold or platinum, rarer than uranium!

Again General Electric starts with raw material — tungsten ore right from the mine. This is reduced to powder, purified, pressed, heated, hammered, drawn through diamond dies until it is a strand as thin as a human hair. For some smaller bulbs, the wire is so fine that its diameter cannot be determined accurately by regular measuring techniques. The effective thickness is reached by weighing a precisely defined length of wire.

In early bulbs, filaments contained only three large loops. GE lamp engineers learned that the more coils in a length of wire the more light it produced per watt. Today's lamp filament is tightly coiled — 850 times. Then this coiled wire is itself coiled again. The coiled-coil design was developed in General Electric laboratories.

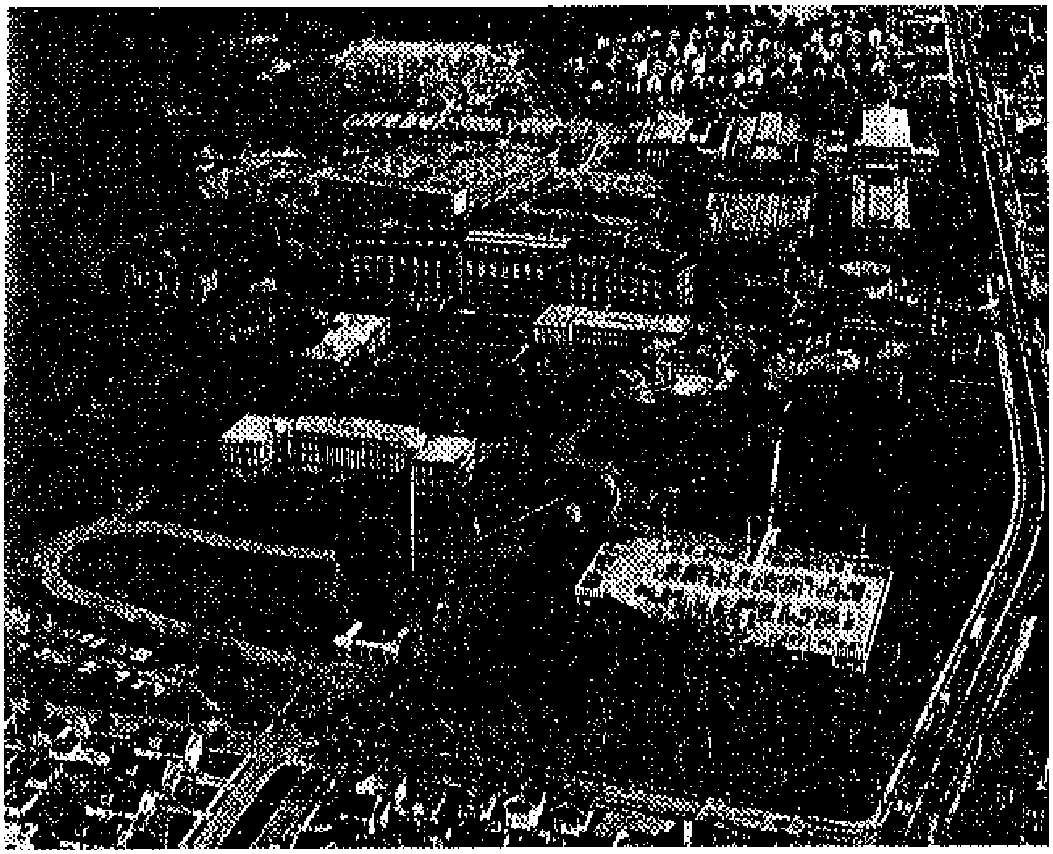
No part of a light bulb is manufactured with more care than its vital tungsten filament. Each one has been closely inspected by the operator of a projection microscope, has been subjected to 20 different tests. Coils out of line as little as 1/10,000 of an inch are rejected.

Early light bulbs operated in a vacuum that kept the filament from evaporating rapidly. GE found that by operating the filament in inert gases, it could retard the evaporation further.

ASSURING BULB QUALITY

A bulb's atmosphere must be spectroscopically pure. One ten-millionth of a per cent of impurity can adversely affect a lamp's operation. General Electric produces its own gases — argon and nitrogen — for incandescent bulbs through a process called "fractional distillation of air." The gas lets the filament operate at temperatures close to melting point — 6170° Fahrenheit — with minimum evaporation.

Other components of a bulb — molybdenum wires to support the filament, Dumet wire leading electric current into the bulb, internal glass parts, threaded aluminum base which fits a variety of new and old sockets — all must be made with the same care before the finally assembled bulb, after many inspections and tests, is lighted and placed in its package. So, although a light bulb is commonplace, it is anything but ordinary!



Nela Park is the national headquarters and the research and development center of the General Electric Company's Lamp Division.

The first of this country's industrial parks, Nela Park was established in 1913 on a plot of land that since has grown to 92 acres, in East Cleveland, Ohio, nine miles from downtown Cleveland.

Here sweeping lawns, ivy-clad Georgian buildings and ornamental trees and shrubs create the atmosphere of a college campus. It is not surprising that this world headquarters of lamp and lighting progress is frequently called "The University of Light."

But Nela Park is more than lawns, buildings and trees; it is people. It is a research scientist experimenting with a new light source for tomorrow, a specialist refining the production techniques of today, an engineer developing a more effective lamp application, a lighting educator demonstrating the world of illumination. Nela Park blends people and products into a responsive combination designed to serve people at work, at home and at play.

LAMP DIVISION

GENERAL ELECTRIC

112-9182