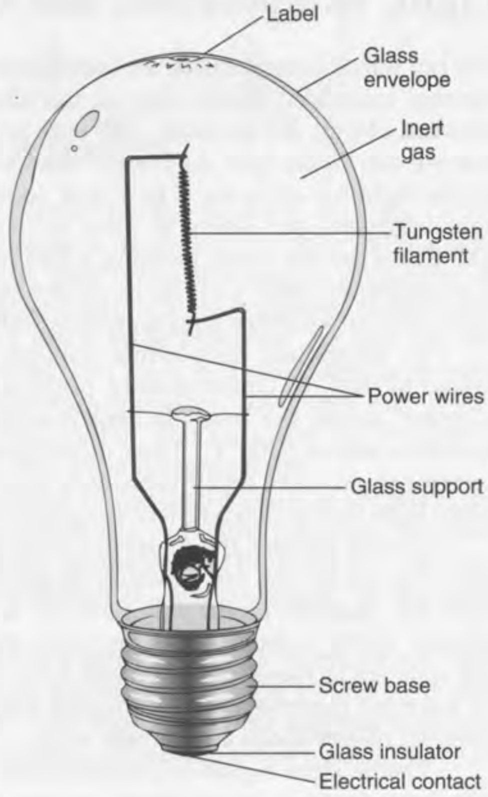

Section 6.3

Incandescent Light Bulbs

For more than a century, incandescent light bulbs have provided light at the flip of a switch. Their invention brought to a close the era of candles and gaslights and spurred the development of electric power. While the variety of incandescent bulbs has grown over the years to include everything from heat lamps to halogen headlights, all incandescent bulbs have at their hearts one simple object: an extremely hot wire filament.

Questions to Think About: *What part of a light bulb emits the light? How is a light bulb similar to a fire or a candle? How do they differ? What colors of light can a plain, unpainted light bulb emit? Why does the top of a light bulb darken with age? What happens when a light bulb burns out?*

Experiments to Do: *Take a look at a few incandescent light bulbs. Try turning one on and off. Are the transitions instantaneous? Stand in a darkened room with your eyes closed and open your eyes suddenly, just after you turn the bulb off. Can you see the bulb going dark? How do its brightness and color change with time?*

Compare the color of the light from a conventional bulb with that from an extended life bulb. Which one produces a better simulation of sunlight? Which bulb should you use in your desk lamp? in an inaccessible ceiling lamp?

Now compare both bulbs with a halogen bulb. How do their colors differ? Which bulb do you expect to live the longest in normal use? Is it surprising that halogen bulbs live longer than conventional bulbs?

Light, Temperature, and Color

The hot wire filament inside an incandescent bulb emits visible light as part of its thermal radiation. While most of the electromagnetic waves that transfer heat between objects are invisible, our eyes are sensitive to a narrow range of waves that we call *visible light*. Any object that is hotter than about 400° C emits enough visible light for us to see it in a dark room. At higher temperatures, that visible light brightens and shifts in color from red to orange to yellow to white. At 500° C, we see the object glowing a dull red. At 1700° C, it emits the orange light of a candle. By 5800° C, it gives off the same brilliant white light as the sun, because the sun's surface temperature is 5800° C.

Fig. 6.3.1 - As you increase the power to an incandescent light bulb, its filament becomes hotter and emits a brighter and whiter light. The cooler filament on the left is dim and red while the hotter one on the right is bright and yellow-white.

To reproduce pure white sunlight, the bulb's filament should also be heated to 5800° C. Unfortunately, nothing is solid at that high temperature. Even tungsten metal, the best filament material known, evaporates quickly at temperatures above 2500° C. Thus incandescent light bulbs operate at lower temperatures and can't really reproduce sunlight. Most give off the warm, orange-white light that is characteristic of tungsten metal at 2500° C.

As you can see, the filament's brightness and color depend on its temperature (Fig. 6.3.1). We can measure brightness as the number of watts of visible light the filament emits. But how do we characterize color and what distinguishes visible light from the invisible forms of electromagnetic radiation? The full answers to these questions will have to wait until Chapters 14 and 15, when we examine electromagnetic radiation and light in detail, but we can make a few essential observations about them now.

Visible light is part of a continuous spectrum of electromagnetic radiation that extends from radio waves at one extreme to gamma rays at the other (Fig. 6.3.2). Different types of electromagnetic radiation are distinguished by their **wavelengths**; that is, the distance between their wave crests. Wavelength is easy to see in the waves on a lake or sea, where the crests are visible and you can directly measure the distance from one to the other. Though electromagnetic waves are not so easy to see, they also have crests and it's possible to measure their spacings.

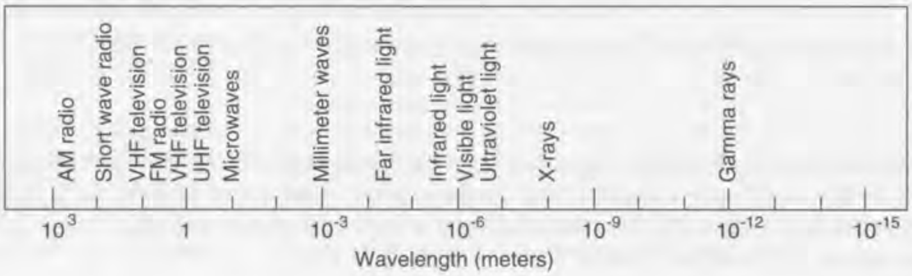

Fig. 6.3.2 - The spectrum of electromagnetic radiation, arranged by wavelength. The scale here is logarithmic, meaning that the wavelength decreases by a factor of ten with each tick mark to the right.

The electromagnetic radiation produced by a hot filament is mostly infrared, visible, and ultraviolet light. While this light is just a tiny portion of the overall electromagnetic spectrum, it's particularly important to our everyday world. Figure 6.3.3 gives an expanded view of the visible portion of the electromagnetic spectrum. Various colors that we see actually correspond to specific wavelength ranges. For example, light with a wavelength of 530 nanometers (billionths of a meter, abbreviated nm) appears green to our eyes.

But the thermal radiation emitted by a filament isn't a single electromagnetic wave with one specific wavelength. Instead, it is many individual waves that cover a broad range of wavelengths. Some of these waves are red light, some green, some blue, and some are invisible.

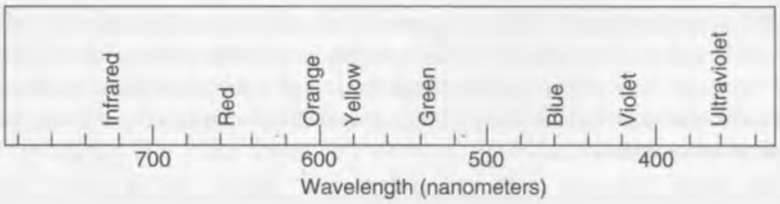

Fig. 6.3.3 - A portion of the electromagnetic radiation spectrum around visible light. Wavelengths are measured in nanometers (nm or billionths of a meter).

The distribution of wavelengths emitted by the filament depends on its temperature and surface properties, particularly its emissivity. Since the filament is essentially black, it emits and absorbs light efficiently and its emissivity is nearly 1. The distribution of wavelengths emitted by a black object is determined by its temperature alone and is called a **black body spectrum**. As you can see from the examples in Fig. 6.3.4, the spectrum of a black body brightens and shifts toward shorter wavelength as its temperature increases. An object that is not black emits somewhat less thermal radiation, but that radiation still brightens and shifts toward shorter wavelength as the object becomes hotter.

Our eyes make an average assessment of the distribution of wavelengths emitted by a black object and we observe reddish, orangish, yellowish, whitish, or bluish light, depending on the object's temperature (Table 6.3.1). The temperature associated with a particular distribution of wavelengths is the **color temperature** of that light.

We can already see two of the principal shortcomings of incandescent light bulbs: their poor efficiency at converting electric energy into visible light and their low color temperature. At 2500° C, only about 5% of the thermal radiation they emit is visible light. The rest is invisible infrared light. They would have to

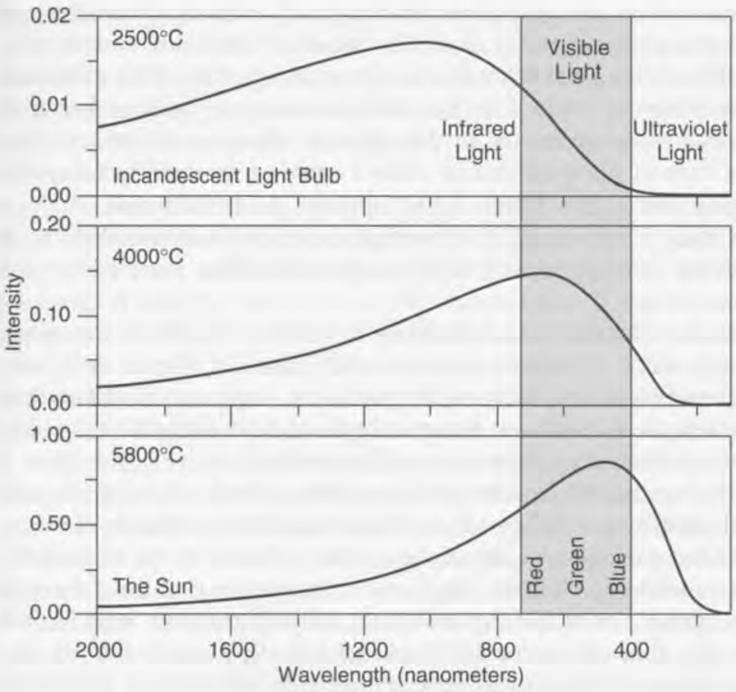

Fig. 6.3.4 - The distributions of light emitted by black objects at 2500° C (top), 4000° C (middle), and 5800° C (bottom). In addition to containing a larger fraction of visible light, the 5800° C object is much brighter than the 2500° C object (note the different intensity scales).

Object	*Temperature*	*Color*
Heat Lamp	500° C	Dull Red
Candle Flame	1700° C	Dim Orange
Bulb Filament	2500° C	Bright Yellow-White
Sun's Surface	5800° C	Brilliant White
Blue Star	>6000° C	Dazzling Blue-White

Table 6.3.1 - The temperatures and colors of light emitted by hot objects.

reach 5000° C before most of their thermal radiation would be visible. Moreover, their 2500° C color temperature makes them look yellowish when compared to sunlight because they don't emit enough blue light. Most of the developments in lighting over the past half century have focused on improving energy efficiency and color temperature.

CHECK YOUR UNDERSTANDING #1:

Satellites can measure the temperatures of agricultural regions from space, looking for signs of crop distress and disease. How do they make such measurements?

The Filament

The bulb's filament is heated by a current of electrically charged particles. These particles flow through the filament, where most of their electric energy is converted into thermal energy. The filament's temperature rises until it radiates away thermal energy as quickly as the electricity produces more. But while the concept of an incandescent bulb is simple, finding a material that can tolerate extremely high temperatures is not.

Early filaments were made of carbon and platinum. Of these materials, carbon showed the most promise. In 1879, Thomas Edison developed an incandescent lamp with a carbon filament that survived for several hundred hours. His was not the first incandescent bulb but rather the first practical incandescent bulb.

However, while carbon has the highest melting temperature of any element (3550° C), it evaporates atoms directly from the solid at much lower temperatures. This process by which a solid turns directly into a gas is called **sublimation** and occurs because individual atoms can occasionally gather together enough thermal energy to break free from the material. Because of carbon's tendency to sublime, a carbon filament that is heated close to its melting temperature quickly disappears as a gas. When a gap appears in the filament, it stops carrying electricity and "burns out." Furthermore, carbon is flammable, so it must be enclosed in an air-tight glass bulb that contains either inert gases or a vacuum.

A better choice for filaments, now used in virtually all modern incandescent bulbs, is tungsten metal. Tungsten melts at 3410° C and sublimes only very slowly at temperatures below this melting temperature. Tungsten filaments can be heated to higher temperatures than carbon filaments before the rate of sublimation becomes intolerable. Since a tungsten filament bulb runs hotter than a carbon filament bulb, it produces a richer, whiter light; more like that of the sun. Like carbon, hot tungsten burns in air and must be protected in a glass bulb.

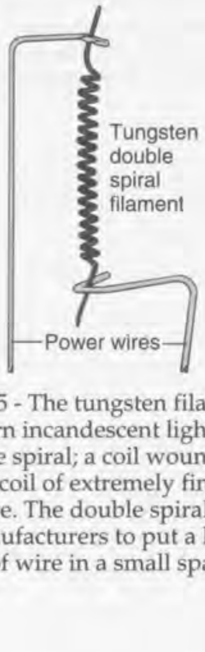

Fig. 6.3.5 - The tungsten filament of a modern incandescent light bulb is a double spiral; a coil wound from a smaller coil of extremely fine tungsten wire. The double spiral allows the manufacturers to put a long length of wire in a small space.

To ensure that most of the electric energy passing through the filament is converted into thermal energy, the filament must be long and thin. A typical 60 W light bulb has about 2 m of 25 microns (0.001 inches) tungsten wire, coiled up into a filament only about 2 cm long. To minimize the filament's length, it's wound into a double spiral. First it's wound into a thin spring-like coil about 0.25 mm wide. This coil is itself wound into a spring-like coil to form the actual filament (Fig. 6.3.5). Fabricating such a complicated tungsten filament is so difficult that it was not accomplished until 1937.

To keep the white hot filament from burning or subliming, it's surrounded by inert gas in a glass bulb. The inert gas, which is mostly argon and contains no oxygen, slows sublimation by bouncing some of the escaping tungsten atoms back onto the filament. While this inert gas extends the filament's life, it wastes energy by permitting conduction and convection to carry heat away from the filament. Tiny tungsten particles that form in this inert gas also rise with convection currents to produce a dark spot on the top of the bulb.

Krypton-filled bulbs transfer less heat from the filament to the envelope because krypton gas is a poor conductor of heat. Such bulbs are more energy efficient than conventional argon-filled bulbs, but they are also more expensive. Krypton is a rare inert gas that is present in the atmosphere at the level of about one part in a million. Krypton bulbs are used in flashlights where the energy efficiency of the lamp is critical to battery life.

CHECK YOUR UNDERSTANDING #2: Here Today, Gone Tomorrow

Snow often disappears from the ground of a period of weeks, even when the temperature remains below freezing. How does the snow disappear?

Extended Life, Halogen, and Three-Way Bulbs

Another way to increase the life of the filament is to make it longer than normal. This change spreads the thermal energy out more so that the filament doesn't get quite as hot and doesn't sublime as quickly. The result is an extended life bulb. Unfortunately, such a bulb is dimmer and redder than a conventional bulb and also less energy efficient. Because an extended life bulb produces less visible light than a conventional bulb, the extended life bulb must have a higher wattage to give equal lighting. Thus extended life bulbs aren't always a bargain. The money you save by not having to replace the bulb so often may well be spent on increased energy costs.

If you make the filament even longer, its temperature will be so low that the bulb will emit the dull, red glow of a heat lamp. Most of the light energy will be in the infrared range, too red for our eyes to see. Nonetheless, you can feel this radiation as heat. Because the filament in a heat lamp runs at a low temperature, it lasts indefinitely.

On the other hand, some bulbs use shorter filaments that operate very near the melting temperature of tungsten. Photoflood lamps used in photography attempt to mimic sunlight by using a very hot filament and a blue-tinted glass housing. While they live only a few hours, these bulbs are able to reach a color temperature as high as 4500° C. The filament itself is not actually that hot but the blue glass allows the lamp to imitate the light of a black object at 4500° C. This high color temperature is important for color photography because normal incandescent illumination gives pictures an orangish appearance.

A halogen bulb also produces whiter light than a normal incandescent bulb, but without the short life of a photoflood. The halogen bulb uses a chemical trick to rebuild its filament continuously during operation. The filament is enclosed in a small tube of quartz or aluminosilicate glass, which can tolerate high temperatures and reactive chemicals (Fig. 6.3.6). This tube contains molecules of the halogen element bromine, or sometimes iodine. During operation, the small tube becomes extremely hot and the halogen reacts with any tungsten atoms on the inside surface of the tube. They form a gas of tungsten-halogen molecules that drift around the tube. When they encounter the white hot filament, these molecules are torn apart and the tungsten atoms stick to the filament.

Fig. 6.3.6 - These halogen bulbs operate at higher temperatures than normal incandescent bulbs and produce whiter light. The large glass envelope of the upper bulb protects a smaller lamp inside.

The halogens act as scavengers, seeking out stray tungsten atoms and returning them to the filament. Although the tungsten filament continues to sublime, the halogens keep bringing the tungsten atoms back. Unfortunately, this rebuilding process slowly changes the structure of the filament. The returning tungsten atoms deposit unevenly on the filament, so that it gradually develops

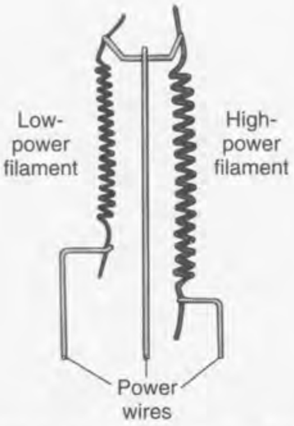

Fig. 6.3.7 - A three-way bulb has two independent filaments. The filament on the left is shorter and thinner than the one on the right and emits about half as much light. The three different light levels correspond to having the left filament on, the right filament on, and both filaments on.

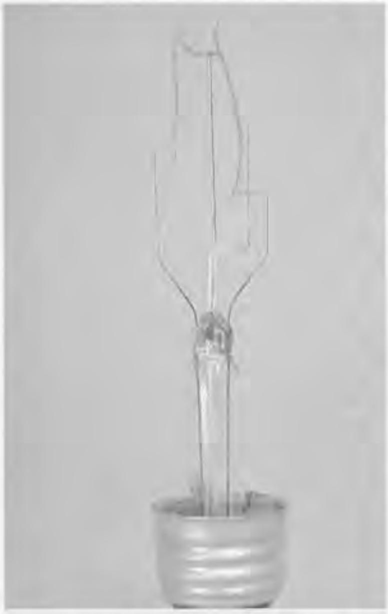

Fig. 6.3.8 - The glass envelope of this three-way light bulb has been removed to expose its two filaments. The shorter, thinner filament (left) uses 50 W, while the longer, thicker one (right) uses 100 W.

thin spots and eventually burns out. Nonetheless, the filament lasts so much longer than in a conventional bulb that it can run several hundred degrees hotter and still have a life of more than 2000 hours. This higher filament temperature allows halogen lamps to produce a whiter light than conventional bulbs with an increased energy efficiency.

Halogen bulbs do have some drawbacks. First, the quartz glass tube is small, extremely hot, and filled with toxic halogen gas. It's a fire and safety hazard, which is why it's often protected by an outer glass tube. Second, the quartz tube is sensitive to fingerprints, which discolor and damage it when it becomes hot. Third, the tungsten recycling system only functions at high temperatures. When a halogen lamp operates on a dimmer at less than full power, tungsten can accumulate on the quartz tube, darkening the bulb and reducing its life. The bulb needs to operate at full power periodically to clean off the quartz tube and return the tungsten to the filament.

Bulbs with different rated powers have different sized filaments. The filament of a 100 W bulb is four times as large as that of a 25 W bulb and emits four times as much light. Unlike the elongated filament of a cool-running extended life bulb, the filament of the 100 W bulb is both longer *and thicker* than that of the 25 W bulb. The 100 W filament draws four times as much electric power as the 25 W filament so that they both operate at the same temperature and emit light with the same color temperature.

One way to make an incandescent bulb with a variable light output is to divide the filament into several parts that can be turned on or off independently. A "three-way bulb" has two independent filaments (Figs. 6.3.7 and 6.3.8). In a typical three-way bulb, a 50-100-150 W bulb, one filament uses 50 W of electric power and the other filament uses 100 W. They are wired so that electric currents can flow through either filament separately or through both filaments simultaneously. If only the low power filament is on, the bulb appears to be a 50 W bulb. If only the high power filament is on, it appears to be a 100 W bulb. If both filaments are on, the bulb appears to be a 150 W bulb. Since the two filaments can burn out separately, the bulb fails by going from having three light levels to only one.

CHECK YOUR UNDERSTANDING #3: Double Wrapping

If you look inside a car's halogen headlight, you will see another small, clear bulb. Why does the manufacturer go to the trouble of putting two separate glass bulbs around the filament?

Summary

How Incandescent Light Bulbs Work: An incandescent light bulb produces light as thermal radiation from an extremely hot tungsten filament. The filament is heated by a steady stream of electrically charged particles passing through it. To prevent the tungsten filament from burning up, it's enclosed in a glass bulb filled with an inert gas.

The spectrum of light emitted by the filament depends on its temperature. The hotter the filament, the whiter its light. Atoms in the filament sublime during operation and the filament slowly disappears. Eventually it becomes so thin that it breaks. The tungsten filament of a normal bulb operates at 2500° C because it would burn out too quickly at higher temperatures. Reducing the operating temperature, as is done in an extended life bulb, prolongs the filament's life at the expense of color temperature and energy efficiency. In contrast, adding halogen gas actually increases the filament's life and improves both the color temperature and energy efficiency.

The Physics of Incandescent Light Bulbs

1. All objects emit thermal electromagnetic radiation. Electromagnetic radiation is characterized by its wavelength, which is what distinguishes between infrared, visible, and ultraviolet light.

2. The distribution of wavelengths in the thermal radiation emitted by a black object, an object with an emissivity of 1, is determined only by its temperature. As its temperature increases, its thermal radiation brightens and shifts toward shorter wavelengths.

3. An object that is not black has an emissivity of less than 1 and emits less thermal radiation than it would if it were black. However, that thermal radiation still brightens and shifts toward shorter wavelengths as the object heats up.

4. When the distribution of wavelengths emitted by a light source is equal to that emitted by a black object at a particular temperature, the black object's temperature is the source's color temperature.

5. The hotter the object, the more visible and ultraviolet light it emits. Below about 5000° C, a black object emits most of its thermal energy as infrared light.

6. Many solids can sublime directly into gases at temperatures near their melting points. This process occurs because individual atoms or molecules occasionally accumulate enough thermal energy to break free from their neighbors and leave the material.

Check Your Understanding - Answers

1. These satellites can measure the wavelength distributions of thermal radiation emitted by various patches of land and determine their temperatures.

Why: Even objects that are near room temperature emit thermal radiation, although this radiation is entirely in the infrared. While the land is not really black, the infrared light it emits is still an accurate indication of its temperature. A satellite can sense the exact form of the distribution and determine the temperature with great accuracy.

2. The snow sublimes to form water vapor in the air.

Why: Ice sublimes quickly at temperatures near its melting temperature, going from a solid to a gas without ever become liquid water.

3. The inner bulb aids the tungsten recycling process while the outer bulb directs the light and protects the inner bulb.

Why: The inner bulb must get hot enough for the halogen gas to react with and recycle the tungsten atoms on its surface. The outer bulb projects the light forward and ensures that nothing touches the hot inner bulb.

Glossary

black body spectrum The distribution of thermal electromagnetic radiation emitted by a black object. This distribution is the amount of radiation emitted at each wavelength and depends only on the temperature of the black object.

color temperature The temperature at which a black object will emit thermal electromagnetic radiation with a particular distribution of wavelengths.

sublimation The process by which atoms or molecules go directly from a solid to a gas.

wavelength A structural characteristic of a wave, corresponding to the distance separating adjacent peaks or troughs.

Review Questions

1. Which is hotter: a black body that is glowing red or one that is glowing blue? Why?

2. If an incandescent bulb only converts a few percent of the electric energy it receives into visible light, what becomes of the rest of this energy?

3. How can a hot filament gradually disappear without the filament ever melting?

4. Why do halogen car headlights produce brighter, whiter light than conventional headlights?

5. Why are extended life bulbs less energy efficient than conventional bulbs?

6. Why does a typical lamp bulb have to be replaced every year or two?

7. Why is there a glass bulb around the tungsten filament of an incandescent light bulb?

Exercises

1. Mothballs are made from a white solid (naphthalene) that has a strong odor. If you leave a mothball out, it slowly disappears. What happens to the mothball?

2. You have a table lamp with a dimmer switch. The dimmer allows you to adjust the temperature and brightness of the lamp's incandescent bulb from very dim red up to brilliant yellow-white. How does the bulb's energy efficiency, the amount of visible light it produces per unit of power consumed, depend on the dimmer's setting?

3. A biologist is studying nocturnal animals with a camera that records infrared light. What differences in this infrared light can the camera look for in order to distinguish the warmer animals from their cooler surroundings?

4. How would you estimate the temperature of a glowing coal in a fireplace?

5. The strongest evidence for the Big Bang theory of the origin of the universe is the thermal radiation emitted by that explosion. This radiation has cooled over the years to only 3° K and is now mostly microwaves. Why should 3° K thermal radiation be microwaves?

6. The heating element of a toaster glows red when it's on. About how hot is that element?

7. A metallurgist measures the temperature of hot metal by comparing its thermal radiation with that from a test object at a known temperature. Explain why this technique works.

8. A light bulb burns out when a small portion of its thinning filament overheats and vaporizes. Why is this event accompanied by a bright flash of blue-white light?

9. Frozen vegetables will "freeze dry" if they're left in cold, dry air. How can water molecules leave the frozen vegetables?

10. Astronomers can tell the surface temperature of a distant star without visiting it. How is this done?

11. When you operate a 50-100-150 W three-way bulb at its 50 W setting, it emits yellow-white light. When you use a dimmer to operate a regular 150 W bulb on only 50 W of electric power, it emits orangish light. Explain the difference.

12. A doctor can study a patient's circulation by imaging the infrared light emitted by the patient's skin. Tissue with poor blood flow is relatively cool. What changes in the infrared emissions would indicate such a cool spot?

13. The 100 W filament in a three-way bulb has twice the surface area of the 50 W filament. Both filaments operate at the same temperature. Why does the 100 W filament emit twice as much thermal radiation as the 50 W filament?

14. Which device delivers more heat per second into a windowless room: a 100 W space heater or a 100 W incandescent light bulb?

15. The chemical reactions that allow a halogen bulb to rebuild its filament only occur at high temperatures. Use the concept of activation energy to explain this behavior.

16. The filament of an incandescent bulb is quite small, yet it emits as much as 100 W of thermal radiation. That's almost as much as your whole body emits. What accounts for the strength of the filament's thermal radiation?