## Summary

**Internal energy**, $U$, refers to the total energy of all the molecules in an object. For an ideal monatomic gas,

$$U = \tfrac{3}{2}NkT = \tfrac{3}{2}nRT \tag{14–1}$$

where $N$ is the number of molecules or $n$ is the number of moles.

**Heat** refers to the transfer of energy from one object to another because of a difference of temperature. Heat is thus measured in energy units, such as joules.

Heat and internal energy are also sometimes specified in calories or kilocalories (kcal), where

$$1\text{ kcal} = 4.186\text{ kJ}$$

is the amount of heat needed to raise the temperature of 1 kg of water by 1 C°.

The **specific heat**, $c$, of a substance is defined as the energy (or heat) required to change the temperature of unit mass of substance by 1 degree; as an equation,

$$Q = mc\,\Delta T, \tag{14–2}$$

where $Q$ is the heat absorbed or given off, $\Delta T$ is the temperature increase or decrease, and $m$ is the mass of the substance.

When heat flows between parts of an isolated system, conservation of energy tells us that the heat gained by one part of the system is equal to the heat lost by the other part of the system. This is the basis of **calorimetry**, which is the quantitative measurement of heat exchange.

Exchange of energy occurs, without a change in temperature, whenever a substance changes phase. The **heat of fusion** is the heat required to melt 1 kg of a solid into the liquid phase; it is also equal to the heat given off when the substance changes from liquid to solid. The **heat of vaporization** is the energy required to change 1 kg of a substance from the liquid to the vapor phase; it is also the energy given off when the substance changes from vapor to liquid.

Heat is transferred from one place (or object) to another in three different ways: conduction, convection, and radiation.

In **conduction**, energy is transferred from molecules or electrons with higher kinetic energy to lower-KE neighbors when they collide.

**Convection** is the transfer of energy by the mass movement of molecules over considerable distances.

**Radiation**, which does not require the presence of matter, is energy transfer by electromagnetic waves, such as from the Sun. All objects radiate energy in an amount that is proportional to the fourth power of their Kelvin temperature ($T^4$) and to their surface area. The energy radiated (or absorbed) also depends on the nature of the surface (dark surfaces absorb and radiate more than do bright shiny ones), which is characterized by the emissivity, $e$.

Radiation from the Sun arrives at the surface of the Earth on a clear day at a rate of about 1000 W/m$^2$.

## Questions

**1.** What happens to the work done when a jar of orange juice is vigorously shaken?

**2.** When a hot object warms a cooler object, does temperature flow between them? Are the temperature changes of the two objects equal?

**3.** (*a*) If two objects of different temperatures are placed in contact, will heat naturally flow from the object with higher internal energy to the object with lower internal energy? (*b*) Is it possible for heat to flow even if the internal energies of the two objects are the same? Explain.

**4.** In warm regions where tropical plants grow but the temperature may drop below freezing a few times in the winter, the destruction of sensitive plants due to freezing can be reduced by watering them in the evening. Explain.

**5.** The specific heat of water is quite large. Explain why this fact makes water particularly good for heating systems (that is, hot-water radiators).

**6.** Why does water in a metal canteen stay cooler if the cloth jacket surrounding the canteen is kept moist?

**7.** Explain why burns caused by steam on the skin are often more severe than burns caused by water at 100°C.

**8.** Explain why water cools (its temperature drops) when it evaporates, using the concepts of latent heat and internal energy.

**9.** Will potatoes cook faster if the water is boiling faster?

**10.** Does an ordinary electric fan cool the air? Why or why not? If not, why use it?

**11.** Very high in the Earth's atmosphere, the temperature can be 700°C. Yet an animal there would freeze to death rather than roast. Explain.

**12.** Explorers on failed Arctic expeditions have survived by covering themselves with snow. Why would they do that?

**13.** Why is wet sand at the beach cooler to walk on than dry sand?

**14.** If you hear that an object has "high heat content," does that mean that its temperature is high? Explain.

**15.** When hot-air furnaces are used to heat a house, why is it important that there be a vent for air to return to the furnace? What happens if this vent is blocked by a bookcase?

**16.** Ceiling fans are sometimes reversible, so that they drive the air down in one season and pull it up in another season. Which way should you set the fan for summer? For winter?

**17.** Down sleeping bags and parkas are often specified as so many inches or centimeters of *loft*, the actual thickness of the garment when it is fluffed up. Explain.

**18.** Microprocessor chips have a "heat sink" glued on top that looks like a series of fins. Why is it shaped like that?

**19.** Sea breezes are often encountered on sunny days at the shore of a large body of water. Explain in light of the fact that the temperature of the land rises more rapidly than that of the nearby water.

**20.** The floor of a house on a foundation under which the air can flow is often cooler than a floor that rests directly on the ground (such as a concrete slab foundation). Explain.

**21.** A 22°C day is warm, while a swimming pool at 22°C feels cool. Why?

**22.** Explain why air temperature readings are always taken with the thermometer in the shade.

**23.** A premature baby in an incubator can be dangerously cooled even when the air temperature in the incubator is warm. Explain.

24. Why is the liner of a thermos bottle silvered (Fig. 14–15), and why does it have a vacuum between its two walls?

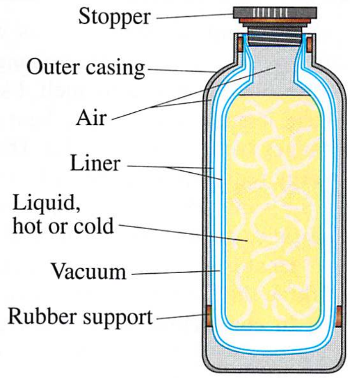


**FIGURE 14–15**
Question 24.

25. Imagine you have a wall that is very well insulated—it has a very high thermal resistance, $R_1$. Now you place a window in the wall that has a relatively low $R$-value, $R_2$. What has happened to the overall $R$-value of the wall plus window, compared to $R_1$ and $R_2$? [*Hint*: The temperature *difference* across the wall is still the same everywhere.]

26. Heat loss occurs through windows by the following processes: (1) ventilation around edges; (2) through the frame, particularly if it is metal; (3) through the glass panes; and (4) radiation. (*a*) For the first three, what is (are) the mechanism(s): conduction, convection, or radiation? (*b*) Heavy curtains reduce which of these heat losses? Explain in detail.

27. A piece of wood lying in the Sun absorbs more heat than a piece of shiny metal. Yet the wood feels less hot than the metal when you pick it up. Explain.

28. The Earth cools off at night much more quickly when the weather is clear than when cloudy. Why?

29. An "emergency blanket" is a thin shiny (metal coated) plastic foil. Explain how it can help to keep an immobile person warm.

30. Explain why cities situated by the ocean tend to have less extreme temperatures than inland cities at the same latitude.

## Problems

### 14–1 Heat as Energy Transfer

1. (I) How much heat (in joules) is required to raise the temperature of 30.0 kg of water from 15°C to 95°C?

2. (I) To what temperature will 7700 J of heat raise 3.0 kg of water that is initially at 10.0°C?

3. (II) An average active person consumes about 2500 Cal a day. (*a*) What is this in joules? (*b*) What is this in kilowatt-hours? (*c*) Your power company charges about a dime per kilowatt-hour. How much would your energy cost per day if you bought it from the power company? Could you feed yourself on this much money per day?

4. (II) A British thermal unit (Btu) is a unit of heat in the British system of units. One Btu is defined as the heat needed to raise 1 lb of water by 1 F°. Show that

$$1\ \text{Btu} = 0.252\ \text{kcal} = 1055\ \text{J}.$$

5. (II) A water heater can generate 32,000 kJ/h. How much water can it heat from 15°C to 50°C per hour?

6. (II) A small immersion heater is rated at 350 W. Estimate how long it will take to heat a cup of soup (assume this is 250 mL of water) from 20°C to 60°C.

7. (II) How many kilocalories are generated when the brakes are used to bring a 1200-kg car to rest from a speed of 95 km/h?

### 14–3 and 14–4 Specific Heat; Calorimetry

8. (I) An automobile cooling system holds 16 L of water. How much heat does it absorb if its temperature rises from 20°C to 90°C?

9. (I) What is the specific heat of a metal substance if 135 kJ of heat is needed to raise 5.1 kg of the metal from 18.0°C to 31.5°C?

10. (II) Samples of copper, aluminum, and water experience the same temperature rise when they absorb the same amount of heat. What is the ratio of their masses? [*Hint*: See Table 14–1.]

11. (II) A 35-g glass thermometer reads 21.6°C before it is placed in 135 mL of water. When the water and thermometer come to equilibrium, the thermometer reads 39.2°C. What was the original temperature of the water?

12. (II) What will be the equilibrium temperature when a 245-g block of copper at 285°C is placed in a 145-g aluminum calorimeter cup containing 825 g of water at 12.0°C?

13. (II) A hot iron horseshoe (mass = 0.40 kg), just forged (Fig. 14–16), is dropped into 1.35 L of water in a 0.30-kg iron pot initially at 20.0°C. If the final equilibrium temperature is 25.0°C, estimate the initial temperature of the hot horseshoe.

**FIGURE 14–16**
Problem 13.

14. (II) A 215-g sample of a substance is heated to 330°C and then plunged into a 105-g aluminum calorimeter cup containing 165 g of water and a 17-g glass thermometer at 12.5°C. The final temperature is 35.0°C. What is the specific heat of the substance? (Assume no water boils away.)

15. (II) How long does it take a 750-W coffeepot to bring to a boil 0.75 L of water initially at 8.0°C? Assume that the part of the pot which is heated with the water is made of 360 g of aluminum, and that no water boils away.

16. (II) Estimate the Calorie content of 75 g of candy from the following measurements. A 15-g sample of the candy is allowed to dry before putting it in a bomb calorimeter. The aluminum bomb has a mass of 0.725 kg and is placed in 2.00 kg of water contained in an aluminum calorimeter cup of mass 0.624 kg. The initial temperature of the mixture is 15.0°C, and its temperature after ignition is 53.5°C.

17. (II) When a 290-g piece of iron at 180°C is placed in a 95-g aluminum calorimeter cup containing 250 g of glycerin at 10°C, the final temperature is observed to be 38°C. Estimate the specific heat of glycerin.

18. (II) The 1.20-kg head of a hammer has a speed of 6.5 m/s just before it strikes a nail (Fig. 14–17) and is brought to rest. Estimate the temperature rise of a 14-g iron nail generated by 10 such hammer blows done in quick succession. Assume the nail absorbs all the energy.

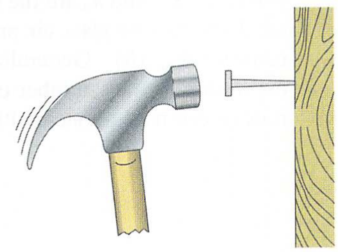

**FIGURE 14–17** Problem 18.

19. (II) A 0.095-kg aluminium sphere is dropped from the roof of a 45-m-high building. If 65% of the thermal energy produced when it hits the ground is absorbed by the sphere, what is its temperature increase?

20. (II) The *heat capacity, C*, of an object is defined as the amount of heat needed to raise its temperature by 1 C°. Thus, to raise the temperature by $\Delta T$ requires heat $Q$ given by

$$Q = C\,\Delta T.$$

(*a*) Write the heat capacity $C$ in terms of the specific heat, $c$, of the material. (*b*) What is the heat capacity of 1.0 kg of water? (*c*) Of 25 kg of water?

## 14–5 Latent Heat

21. (I) How much heat is needed to melt 16.50 kg of silver that is initially at 20°C?

22. (I) During exercise, a person may give off 180 kcal of heat in 30 min by evaporation of water from the skin. How much water has been lost?

23. (I) If $2.80 \times 10^5$ J of energy is supplied to a flask of liquid oxygen at −183°C, how much oxygen can evaporate?

24. (II) A 30-g ice cube at its melting point is dropped into an insulated container of liquid nitrogen. How much nitrogen evaporates if it is at its boiling point of 77 K and has a latent heat of vaporization of 200 kJ/kg? Assume for simplicity that the specific heat of ice is a constant and is equal to its value near its melting point.

25. (II) A cube of ice is taken from the freezer at −8.5°C and placed in a 95-g aluminum calorimeter filled with 310 g of water at room temperature of 20.0°C. The final situation is observed to be all water at 17.0°C. What was the mass of the ice cube?

26. (II) An iron boiler of mass 230 kg contains 830 kg of water at 18°C. A heater supplies energy at the rate of 52,000 kJ/h. How long does it take for the water (*a*) to reach the boiling point, and (*b*) to all have changed to steam?

27. (II) In a hot day's race, a bicyclist consumes 8.0 L of water over the span of four hours. Making the approximation that all of the cyclist's energy goes into evaporating this water as sweat, how much energy in kcal did the rider use during the ride? (Since the efficiency of the rider is only about 20%, most of the energy consumed does go to heat, so our approximation is not far off.)

28. (II) What mass of steam at 100°C must be added to 1.00 kg of ice at 0°C to yield liquid water at 20°C?

29. (II) The specific heat of mercury is 138 J/kg·C°. Determine the latent heat of fusion of mercury using the following calorimeter data: 1.00 kg of solid Hg at its melting point of −39.0°C is placed in a 0.620-kg aluminum calorimeter with 0.400 kg of water at 12.80°C; the resulting equilibrium temperature is 5.06°C.

30. (II) A 70-g bullet traveling at 250 m/s penetrates a block of ice at 0°C and comes to rest within the ice. Assuming that the temperature of the bullet doesn't change appreciably, how much ice is melted as a result of the collision?

31. (II) A 54.0-kg ice-skater moving at 6.4 m/s glides to a stop. Assuming the ice is at 0°C and that 50% of the heat generated by friction is absorbed by the ice, how much ice melts?

32. (II) At a crime scene, the forensic investigator notes that the 8.2-g lead bullet that was stopped in a doorframe apparently melted completely on impact. Assuming the bullet was fired at room temperature (20°C), what does the investigator calculate as the *minimum* muzzle velocity of the gun?

## 14–6 to 14–8 Conduction, Convection, Radiation

33. (I) One end of a 33-cm-long aluminum rod with a diameter of 2.0 cm is kept at 460°C, and the other is immersed in water at 22°C. Calculate the heat conduction rate along the rod.

34. (I) Calculate the rate of heat flow by conduction in Example 14–10, assuming that there are strong gusty winds and the external temperature is −5°C.

35. (I) (*a*) How much power is radiated by a tungsten sphere (emissivity $e = 0.35$) of radius 22 cm at a temperature of 25°C? (*b*) If the sphere is enclosed in a room whose walls are kept at −5°C, what is the *net* flow rate of energy out of the sphere?

36. (II) *Heat conduction to skin.* Suppose 200 W of heat flows by conduction from the blood capillaries beneath the skin to the body's surface area of 1.5 m². If the temperature difference is 0.50 C°, estimate the average distance of capillaries below the skin surface.

37. (II) Two rooms, each a cube 4.0 m per side, share a 12-cm-thick brick wall. Because of a number of 100-W lightbulbs in one room, the air is at 30°C, while in the other room it is at 10°C. How many of the 100-W bulbs are needed to maintain the temperature difference across the wall?

38. (II) How long does it take the Sun to melt a block of ice at 0°C with a flat horizontal area 1.0 m² and thickness 1.0 cm? Assume that the Sun's rays make an angle of 30° with the vertical and that the emissivity of ice is 0.050.

39. (II) A copper rod and an aluminum rod of the same length and cross-sectional area are attached end to end (Fig. 14–18). The copper end is placed in a furnace maintained at a constant temperature of 250°C. The aluminum end is placed in an ice bath held at constant temperature of 0.0°C. Calculate the temperature at the point where the two rods are joined.

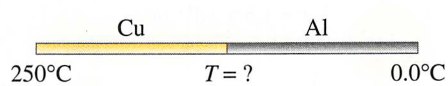


**FIGURE 14–18** Problem 39.

40. (II) (*a*) Using the solar constant, estimate the rate at which the whole Earth receives energy from the Sun. (*b*) Assume the Earth radiates an equal amount back into space (that is, the Earth is in equilibrium). Then, assuming the Earth is a perfect emitter ($e = 1.0$), estimate its average surface temperature.

41. (II) A 100-W lightbulb generates 95 W of heat, which is dissipated through a glass bulb that has a radius of 3.0 cm and is 1.0 mm thick. What is the difference in temperature between the inner and outer surfaces of the glass?

42. (III) Suppose the insulating qualities of the wall of a house come mainly from a 4.0-in. layer of brick and an *R*-19 layer of insulation, as shown in Fig. 14–19. What is the total rate of heat loss through such a wall, if its total area is 240 ft$^2$ and the temperature difference across it is 12 F°?

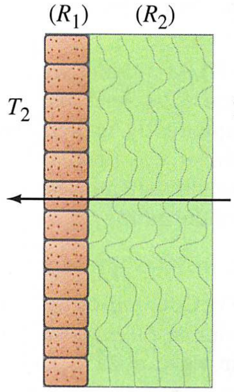


**FIGURE 14–19** Two layers insulating a wall. Problem 42.

43. (III) A double-glazed window has two panes of glass separated by an air space, Fig. 14–20. (*a*) Show that the rate of heat flow through such a window by conduction is given by

$$\frac{Q}{t} = \frac{A(T_2 - T_1)}{l_1/k_1 + l_2/k_2 + l_3/k_3},$$

where $k_1$, $k_2$, and $k_3$ are the thermal conductivities for glass, air, and glass, respectively. (*b*) Generalize this expression for any number of materials placed next to one another.

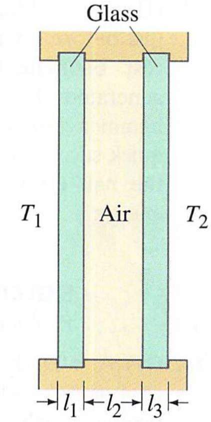


**FIGURE 14–20** Problem 43.

44. (III) Approximately how long should it take 11.0 kg of ice at 0°C to melt when it is placed in a carefully sealed Styrofoam ice chest of dimensions 25 cm × 35 cm × 55 cm whose walls are 1.5 cm thick? Assume that the conductivity of Styrofoam is double that of air and that the outside temperature is 32°C.

## General Problems

45. A soft-drink can contains about 0.20 kg of liquid at 5°C. Drinking this liquid can actually consume some of the fat in the body, since energy is needed to warm the water to body temperature (37°C). How many food Calories should the drink have so that it is in perfect balance with the heat needed to warm the liquid?

46. If coal gives off 30 MJ/kg when it is burned, how much coal would be needed to heat a house that requires $2.0 \times 10^5$ MJ for the whole winter? Assume that 30% of the heat is lost up the chimney.

47. To get an idea of how much thermal energy is contained in the world's oceans, estimate the heat liberated when a cube of ocean water, 1 km on each side, is cooled by 1 K. (Approximate the ocean water as pure water for this estimate.)

48. A 15-g lead bullet is tested by firing it into a fixed block of wood with a mass of 1.05 kg. The block and imbedded bullet together absorb all the heat generated. After thermal equilibrium has been reached, the system has a temperature rise measured as 0.020 C°. Estimate the entering speed of the bullet.

49. (*a*) Find the total power radiated into space by the Sun, assuming it to be a perfect emitter at $T = 5500$ K. The Sun's radius is $7.0 \times 10^8$ m. (*b*) From this, determine the power per unit area arriving at the Earth, $1.5 \times 10^{11}$ m away (Fig. 14–21).

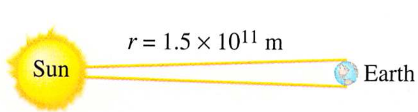


**FIGURE 14–21** Problem 49.

50. During light activity, a 70-kg person may generate 200 kcal/h. Assuming that 20% of this goes into useful work and the other 80% is converted to heat, calculate the temperature rise of the body after 1.00 h if none of this heat were transferred to the environment.

51. A 340-kg marble boulder rolls off the top of a cliff and falls a vertical height of 140 m before striking the ground. Estimate the temperature rise of the rock if 50% of the heat generated remains in the rock.

52. A 2.3-kg lead ball is dropped into a 2.5-L insulated pail of water initially at 20.0°C. If the final temperature of the water–lead combination is 28.0°C, what was the initial temperature of the lead ball?

53. A mountain climber wears a goose down jacket 3.5 cm thick with total surface area 1.2 m$^2$. The temperature at the surface of the clothing is −20°C and at the skin is 34°C. Determine the rate of heat flow by conduction through the jacket (*a*) assuming it is dry and the thermal conductivity *k* is that of down, and (*b*) assuming the jacket is wet, so *k* is that of water and the jacket has matted to 0.50 cm thickness.

54. A marathon runner has an average metabolism rate of about 950 kcal/h during a race. If the runner has a mass of 55 kg, estimate how much water she would lose to evaporation from the skin for a race that lasts 2.5 h.

55. Estimate the rate at which heat can be conducted from the interior of the body to the surface. Assume that the thickness of tissue is 4.0 cm, that the skin is at 34°C and the interior at 37°C, and that the surface area is 1.5 m$^2$. Compare this to the measured value of about 230 W that must be dissipated by a person working lightly. This clearly shows the necessity of convective cooling by the blood.

56. A house has well-insulated walls 17.5 cm thick (assume conductivity of air) and area $410\,\text{m}^2$, a roof of wood 6.5 cm thick and area $280\,\text{m}^2$, and uncovered windows 0.65 cm thick and total area $33\,\text{m}^2$. (*a*) Assuming that heat is lost only by conduction, calculate the rate at which heat must be supplied to this house to maintain its inside temperature at 23°C if the outside temperature is −10°C. (*b*) If the house is initially at 10°C, estimate how much heat must be supplied to raise the temperature to 23°C within 30 min. Assume that only the air needs to be heated and that its volume is $750\,\text{m}^3$. (*c*) If natural gas costs \$0.080 per kilogram and its heat of combustion is $5.4 \times 10^7\,\text{J/kg}$, how much is the monthly cost to maintain the house as in part (*a*) for 24 h each day, assuming 90% of the heat produced is used to heat the house? Take the specific heat of air to be 0.24 kcal/kg·C°.

57. A 15-g lead bullet traveling at 220 m/s passes through a thin wall and emerges at a speed of 160 m/s. If the bullet absorbs 50% of the heat generated, (*a*) what will be the temperature rise of the bullet? (*b*) If the bullet's initial temperature was 20°C, will any of the bullet melt, and if so, how much?

58. A leaf of area $40\,\text{cm}^2$ and mass $4.5 \times 10^{-4}\,\text{kg}$ directly faces the Sun on a clear day. The leaf has an emissivity of 0.85 and a specific heat of 0.80 kcal/kg·K. (*a*) Estimate the rate of rise of the leaf's temperature. (*b*) Calculate the temperature the leaf would reach if it lost all its heat by radiation to the surroundings at 20°C. (*c*) In what other ways can the heat be dissipated by the leaf?

59. Using the result of part (*a*) in Problem 58, take into account radiation from the leaf to calculate how much water must be transpired (evaporated) by the leaf per hour to maintain a temperature of 35°C.

60. An iron meteorite melts when it enters the Earth's atmosphere. If its initial temperature was −125°C outside of Earth's atmosphere, calculate the minimum velocity the meteorite must have had before it entered Earth's atmosphere.

61. The temperature within the Earth's crust increases about 1.0 C° for each 30 m of depth. The thermal conductivity of the crust is 0.80 W/C°·m. (*a*) Determine the heat transferred from the interior to the surface for the entire Earth in 1 day. (*b*) Compare this heat to the amount of energy incident on the Earth in 1 day due to radiation from the Sun.

62. In a typical game of squash (Fig. 14–22), two people hit a soft rubber ball at a wall until they are about to drop due to dehydration and exhaustion. Assume that the ball hits the wall at a velocity of 22 m/s and bounces back with a velocity of 12 m/s, and that the kinetic energy lost in the process heats the ball. What will be the temperature increase of the ball after one bounce? (The specific heat of rubber is about 1200 J/kg·C°.)

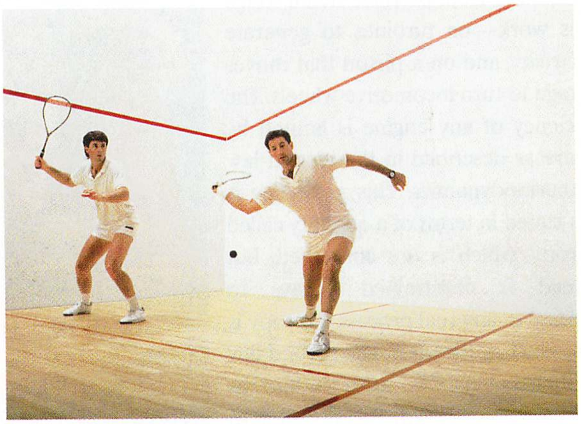

**FIGURE 14–22** Problem 62.

63. What will be the final result when equal masses of ice at 0°C and steam at 100°C are mixed together?

64. In a cold environment, a person can lose heat by conduction and radiation at a rate of about 200 W. Estimate how long it would take for the body temperature to drop from 36.6°C to 35.6°C if metabolism were nearly to stop. Assume a mass of 70 kg. (See Table 14–1.)

65. After a hot shower and dishwashing, there is "no hot water" left in the 50-gal (185-L) water heater. This suggests that the tank has emptied and refilled with water at roughly 10°C. (*a*) How much energy does it take to reheat the water to 50°C? (*b*) How long would it take if the heater output is 9500 W?

66. The temperature of the glass surface of a 60-W lightbulb is 65°C when the room temperature is 18°C. Estimate the temperature of a 150-W lightbulb with a glass bulb the same size. Consider only radiation, and assume that 90% of the energy is emitted as heat.

## Answers to Exercises

**A:** 0.21 kg.

**B:** The drapes trap a layer of air between the outside wall and the room, which acts as an excellent insulator.