the gas is also oxygen but $p_3 = 40$ cm Hg; for C the gas is hydrogen and $p_3 = 30$ cm Hg. The measured values of p for the three thermometers are p_A, p_B, and p_C. (*a*) An approximate value of the room temperature T can be obtained with each of the thermometers using

$$T_A = (273.16\ \text{K})(p_A/20\ \text{cm Hg}),$$

$$T_B = (273.16\ \text{K})(p_B/40\ \text{cm Hg}),$$

$$T_C = (273.16\ \text{K})(p_C/30\ \text{cm Hg}).$$

Mark each of the following statements true or false: (1) With the method described, all three thermometers will give the same value of T. (2) The two oxygen thermometers will agree with each other but not with the hydrogen thermometer. (3) Each of the three will give a different value of T. (*b*) In the event that there is a disagreement among the three thermometers, explain how you would change the method of using them to cause all three to give the same value of T.

10. The editor-in-chief of a well-known business magazine, discussing possible warming effects associated with the increasing concentration of carbon dioxide in the Earth's atmosphere (greenhouse effect), wrote: "The polar regions might be three times warmer than now, ... " What do you suppose he meant, and what did he say literally? (See "Warmth and Temperature: A Comedy of Errors," by Albert A. Bartlett, *The Physics Teacher,* November 1984, p. 517.)
11. Although the absolute zero of temperature seems to be experimentally unattainable, temperatures as low as 0.00000002 K have been achieved in the laboratory. Why would physicists strive, as indeed they do, to obtain still lower temperatures? Isn't this low enough for all practical purposes?
12. You put two uncovered pails of water, one containing hot water and one containing cold water, outside in below-freezing weather. The pail with the hot water will usually begin to freeze first. Why? What would happen if you covered the pails?
13. Can a temperature be assigned to a vacuum?
14. Does our "temperature sense" have a built-in sense of direction; that is, does hotter necessarily mean higher temperature, or is this just an arbitrary convention? Celsius, by the way, originally chose the steam point as 0°C and the ice point as 100°C.
15. Many medicine labels inform the user to store below 86°F. Why 86? (*Hint:* Change to Celsius.) (See *The Science Almanac,* 1985–1986, p. 430.)
16. How would you suggest measuring the temperature of (*a*) the Sun, (*b*) the Earth's upper atmosphere, (*c*) an insect, (*d*) the Moon, (*e*) the ocean floor, and (*f*) liquid helium?
17. Considering the Celsius, Fahrenheit, and Kelvin scales, does any one stand out as "nature's scale"? Discuss.
18. Is one gas any better than another for purposes of a standard constant-volume gas thermometer? What properties are desirable in a gas for such purposes?
19. State some objections to using water-in-glass as a thermometer. Is mercury-in-glass an improvement? If so, explain why.
20. Explain why the column of mercury first descends and then rises when a mercury-in-glass thermometer is put in a flame.
21. What are the dimensions of α, the coefficient of linear expansion? Does the value of α depend on the unit of length used? When Fahrenheit degrees are used instead of Celsius degrees as the unit of temperature change, does the numerical value of α change? If so, how? If not, prove it.
22. A metal ball can pass through a metal ring. When the ball is heated, however, it gets stuck in the ring. What would happen if the ring, rather than the ball, were heated?
23. A bimetallic strip, consisting of two different metal strips riveted together, is used as a control element in the common thermostat. Explain how it works.
24. Two strips, one of iron and one of zinc, are riveted together side by side to form a straight bar that curves when heated. Why is the iron on the inside of the curve?
25. Explain how the period of a pendulum clock can be kept constant with temperature by attaching vertical tubes of mercury to the bottom of the pendulum.
26. Why should a chimney be freestanding, that is, not part of the structural support of the house?
27. Water expands when it freezes. Can we define a coefficient of volume expansion for the freezing process?
28. Explain why the apparent expansion of a liquid in a glass bulb does not give the true expansion of the liquid.
29. Does the change in volume of an object when its temperature is raised depend on whether the object has cavities inside, other things being equal?
30. Why is it much more difficult to make a precise determination of the coefficient of expansion of a liquid than of a solid?
31. A common model of a solid assumes the atoms to be points executing simple harmonic motion about mean lattice positions. What would be the coefficient of linear expansion of such a lattice?
32. Explain the fact that the temperature of the ocean at great depths is very constant the year round, at a temperature of about 4°C.
33. Explain why lakes freeze first at the surface.
34. What causes water pipes to burst in the winter?
35. What can you conclude about how the melting point of ice depends on pressure from the fact that ice floats on water?

PROBLEMS

Section 22-3 Measuring Temperature

1. A *resistance thermometer* is a thermometer in which the electrical resistance changes with temperature. We are free to define temperatures measured by such a thermometer in kelvins (K) to be directly proportional to the resistance R,

measured in ohms (Ω). A certain resistance thermometer is found to have a resistance R of 90.35 Ω when its bulb is placed in water at the triple-point temperature (273.16 K). What temperature is indicated by the thermometer if the bulb is placed in an environment such that its resistance is 96.28 Ω?

2. A thermocouple is formed from two different metals, joined at two points in such a way that a small voltage is produced when the two junctions are at different temperatures. In a particular iron–constantan thermocouple, with one junction held at 0°C, the output voltage varies linearly from 0 to 28.0 mV as the temperature of the other junction is raised from 0 to 510°C. Find the temperature of the variable junction when the thermocouple output is 10.2 mV.

3. The amplification or *gain* of a transistor amplifier may depend on the temperature. The gain for a certain amplifier at room temperature (20.0°C) is 30.0, whereas at 55.0°C it is 35.2. What would the gain be at 28.0°C if the gain depends linearly on temperature over this limited range?

4. Absolute zero is −273.15°C. Find absolute zero on the Fahrenheit scale.

5. If your doctor tells you that your temperature is 310 kelvins above absolute zero, should you worry? Explain your answer.

6. (*a*) The temperature of the surface of the Sun is about 6000 K. Express this on the Fahrenheit scale. (*b*) Express normal human body temperature, 98.6°F, on the Celsius scale. (*c*) In the continental United States, the lowest officially recorded temperature is −70°F at Rogers Pass, Montana. Express this on the Celsius scale. (*d*) Express the normal boiling point of oxygen, −183°C, on the Fahrenheit scale. (*e*) At what Celsius temperature would you find a room to be uncomfortably warm?

7. At what temperature, if any, do the following pairs of scales give the same reading: (*a*) Fahrenheit and Celsius, (*b*) Fahrenheit and Kelvin, and (*c*) Celsius and Kelvin?

8. At what temperature is the Fahrenheit scale reading equal to (*a*) twice that of the Celsius and (*b*) half that of the Celsius?

9. It is an everyday observation that hot and cold objects cool down or warm up to the temperature of their surroundings. If the temperature difference ΔT between an object and its surroundings ($\Delta T = T_{obj} - T_{sur}$) is not too great, the rate of cooling or warming of the object is proportional, approximately, to this temperature difference; that is,

$$\frac{d\,\Delta T}{dt} = -A(\Delta T),$$

where A is a constant. The minus sign appears because ΔT decreases with time if ΔT is positive and increases if ΔT is negative. This is known as *Newton's law of cooling.* (*a*) On what factors does A depend? What are its dimensions? (*b*) If at some instant $t = 0$ the temperature difference is ΔT_0, show that it is

$$\Delta T = \Delta T_0 e^{-At}$$

at a time t later.

10. Early in the morning the heater of a house breaks down. The outside temperature is −7.0°C. As a result, the inside temperature drops from 22 to 18°C in 45 min. How much longer will it take for the inside temperature to fall by another 4.0 C°? Assume that the outside temperature does not change and that Newton's law of cooling applies; see the previous problem.

Section 22-4 The Ideal Gas Temperature Scale

11. If the gas temperature at the steam point is 373.15 K, what is the limiting value of the ratio of the pressures of a gas at the steam point and at the triple point of water when the gas is kept at constant volume?

12. A particular gas thermometer is constructed of two gas-containing bulbs, each of which is put into a water bath, as shown in Fig. 13. The pressure difference between the two bulbs is measured by a mercury manometer as shown in the figure. Appropriate reservoirs, not shown in the diagram, maintain constant gas volume in the two bulbs. There is no difference in pressure when both baths are at the triple point of water. The pressure difference is 120 mm Hg when one bath is at the triple point and the other is at the boiling point of water. Finally, the pressure difference is 90.0 mm Hg when one bath is at the triple point and the other is at an unknown temperature to be measured. Find the unknown temperature.

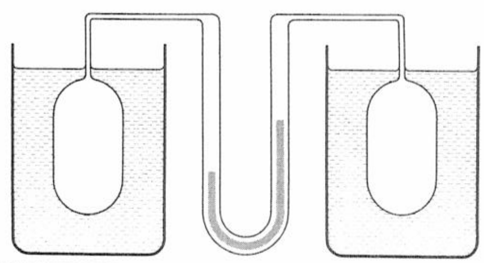

Figure 13 Problem 12.

13. Two constant-volume gas thermometers are assembled, one using nitrogen as the working gas and the other using helium. Both contain enough gas so that $p_{tr} = 100$ cm Hg. What is the difference between the pressures in the two thermometers if both are inserted into a water bath at the boiling point? Which pressure is the higher of the two? See Fig. 5.

Section 22-5 Thermal Expansion

14. An aluminum flagpole is 33 m high. By how much does its length increase as the temperature increases by 15 C°?

15. The Pyrex® glass mirror in the telescope at the Mount Palomar Observatory (the Hale telescope) has a diameter of 200 in. The most extreme temperatures ever recorded on Palomar Mountain are −10°C and 50°C. Determine the maximum change in the diameter of the mirror.

16. A circular hole in an aluminum plate is 2.725 cm in diameter at 12°C. What is its diameter when the temperature of the plate is raised to 140°C?

17. Steel railroad tracks are laid when the temperature is −5.0°C. A standard section of rail is then 12.0 m long. What gap should be left between rail sections so that there is no compression when the temperature gets as high as 42°C?

18. A glass window is 200 cm by 300 cm at 10°C. By how much has its area increased when its temperature is 40°C? Assume that the glass is free to expand.

19. A brass cube has an edge length of 33.2 cm at 20.0°C. Find (*a*) the increase in surface area and (*b*) the increase in volume when it is heated to 75.0°C.

20. What is the volume of a lead ball at -12°C if its volume at 160°C is 530 cm^3?

21. Show that when the temperature of a liquid in a barometer changes by ΔT, and the pressure is constant, the height h changes by $\Delta h = \beta h\, \Delta T$, where β is the coefficient of volume expansion of the liquid. Neglect the expansion of the glass tube.

22. In a certain experiment, it was necessary to be able to move a small radioactive source at selected, extremely slow speeds. This was accomplished by fastening the source to one end of an aluminum rod and heating the central section of the rod in a controlled way. If the effective heated section of the rod in Fig. 14 is 1.8 cm, at what constant rate must the temperature of the rod be made to change if the source is to move at a constant speed of 96 nm/s?

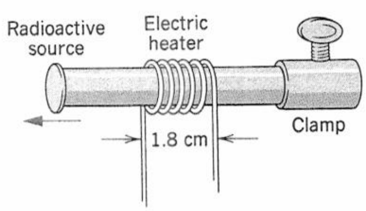

Figure 14 Problem 22.

23. Show that if α is dependent on the temperature T, then

$$L \cong L_0\left[1 + \int_{T_0}^{T} \alpha(T)dT\right],$$

where L_0 is the length at a reference temperature T_0.

24. Soon after the Earth formed, heat released by the decay of radioactive elements raised the average internal temperature from 300 to 3000 K, at about which value it remains today. Assuming an average coefficient of volume expansion of $3.2 \times 10^{-5}\ \text{K}^{-1}$, by how much has the radius of the Earth increased since its formation?

25. A rod is measured to be 20.05 cm long using a steel ruler at a room temperature of 20°C. Both the rod and the ruler are placed in an oven at 270°C, where the rod now measures 20.11 cm using the same ruler. Calculate the coefficient of thermal expansion for the material of which the rod is made.

26. Consider a mercury-in-glass thermometer. Assume that the cross section of the capillary is constant at A, and that V is the volume of the bulb of mercury at 0.00°C. Suppose that the mercury just fills the bulb at 0.00°C. Show that the length L of the mercury column in the capillary at a temperature T, in °C, is

$$L = \frac{V}{A}(\beta - 3\alpha)T,$$

that is, proportional to the temperature, where β is the coefficient of volume expansion of mercury and α is the coefficient of linear expansion of glass.

27. (*a*) Show that if the lengths of two rods of different solids are inversely proportional to their respective coefficients of linear expansion at the same initial temperature, the difference in length between them will be constant at all temperatures. (*b*) What should be the lengths of a steel and a brass rod at 0°C so that at all temperatures their difference in length is 0.30 m?

28. As a result of a temperature rise of 32°C, a bar with a crack at its center buckles upward, as shown in Fig. 15. If the fixed distance $L_0 = 3.77$ m and the coefficient of linear expansion is 25×10^{-6}/C°, find x, the distance to which the center rises.

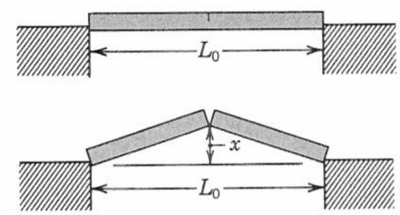

Figure 15 Problem 28.

29. A steel rod is 3.000 cm in diameter at 25°C. A brass ring has an interior diameter of 2.992 cm at 25°C. At what common temperature will the ring just slide onto the rod?

30. The area A of a rectangular plate is ab. Its coefficient of linear expansion is α. After a temperature rise ΔT, side a is longer by Δa and side b is longer by Δb. Show that if we neglect the small quantity $\Delta a\, \Delta b/ab$ (see Fig. 16), then $\Delta A = 2\alpha A\, \Delta T$, verifying Eq. 14.

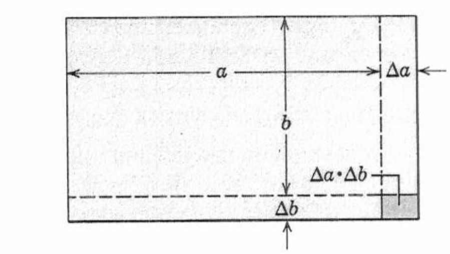

Figure 16 Problem 30.

31. Prove that, if we neglect extremely small quantities, the change in volume of a solid upon expansion through a temperature rise ΔT is given by $\Delta V = 3\alpha V\, \Delta T$, where α is the coefficient of linear expansion. See Eq. 15.

32. When the temperature of a copper penny (which is not pure copper) is raised by 100 C°, its diameter increases by 0.18%. Find the percent increase in (*a*) the area of a face, (*b*) the thickness, (*c*) the volume, and (*d*) the mass of the penny. (*e*) Calculate its coefficient of linear expansion.

33. Density is mass divided by volume. If the volume V is temperature dependent, so is the density ρ. Show that the change in density $\Delta\rho$ with change in temperature ΔT is given by

$$\Delta\rho = -\beta\rho\,\Delta T,$$

where β is the coefficient of volume expansion. Explain the minus sign.

34. When the temperature of a metal cylinder is raised from 60 to 100°C, its length increases by 0.092%. (*a*) Find the percent change in density. (*b*) Identify the metal.

35. At 100°C a glass flask is completely filled by 891 g of mercury. What mass of mercury is needed to fill the flask at −35°C? (The coefficient of linear expansion of glass is 9.0×10^{-6}/C°; the coefficient of volume expansion of mercury is 1.8×10^{-4}/C°.)

36. Figure 17 shows the variation of the coefficient of volume expansion of water between 4°C and 20°C. The density of water at 4°C is 1000 kg/m³. Calculate the density of water at 20°C.

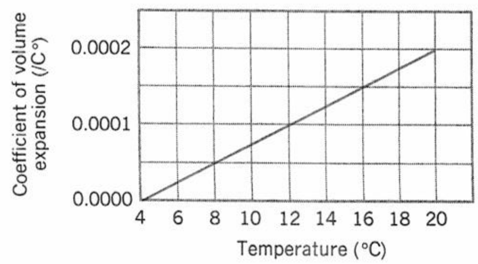

Figure 17 Problem 36.

37. A composite bar of length $L = L_1 + L_2$ is made from a bar of material 1 and length L_1 attached to a bar of material 2 and length L_2, as shown in Fig. 18. (*a*) Show that the effective coefficient of linear expansion α for this bar is given by $\alpha = (\alpha_1 L_1 + \alpha_2 L_2)/L$. (*b*) Using steel and brass, design such a composite bar whose length is 52.4 cm and whose effective coefficient of linear expansion is 13×10^{-6}/C°.

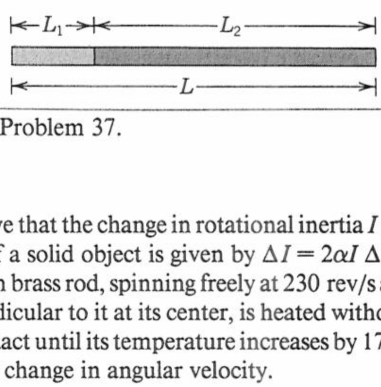

Figure 18 Problem 37.

38. (*a*) Prove that the change in rotational inertia I with temperature of a solid object is given by $\Delta I = 2\alpha I\,\Delta T$. (*b*) A thin uniform brass rod, spinning freely at 230 rev/s about an axis perpendicular to it at its center, is heated without mechanical contact until its temperature increases by 170 C°. Calculate the change in angular velocity.

39. A cylinder placed in frictionless bearings is set rotating about its axis. The cylinder is then heated, without mechanical contact, until its radius is increased by 0.18%. What is the percent change in the cylinder's (*a*) angular momentum, (*b*) angular velocity, and (*c*) rotational energy?

40. (*a*) Prove that the change in period P of a physical pendulum with temperature is given by $\Delta P = \frac{1}{2}\alpha P\,\Delta T$. (*b*) A clock pendulum made of invar has a period of 0.500 s and is accurate at 20°C. If the clock is used in a climate where the temperature averages 30°C, what approximate correction to the time given by the clock is necessary at the end of 30 days?

41. A pendulum clock with a pendulum made of brass is designed to keep accurate time at 20°C. How much will the error be, in seconds per hour, if the clock operates at 0°C?

42. An aluminum cup of 110 cm³ capacity is filled with glycerin at 22°C. How much glycerin, if any, will spill out of the cup if the temperature of the cup and glycerin is raised to 28°C? (The coefficient of volume expansion of glycerin is 5.1×10^{-4}/C°.)

43. A 1.28-m-long vertical glass tube is half-filled with a liquid at 20.0°C. How much will the height of the liquid column change when the tube is heated to 33.0°C? Assume that $\alpha_{\text{glass}} = 1.1 \times 10^{-5}$/C° and $\beta_{\text{liquid}} = 4.2 \times 10^{-5}$/C°.

44. A steel rod at 24°C is bolted securely at both ends and then cooled. At what temperature will it begin to yield? See Table 1, Chapter 14.

45. Three equal-length straight rods, of aluminum, invar, and steel, all at 20°C, form an equilateral triangle with hinge pins at the vertices. At what temperature will the angle opposite the invar rod be 59.95°? See Appendix H for needed trigonometric formulas.

46. Two rods of different materials but having the same lengths L and cross-sectional areas A are arranged end-to-end between fixed, rigid supports, as shown in Fig. 19*a*. The temperature is T and there is no initial stress. The rods are heated, so that their temperature increases by ΔT. (*a*) Show that the rod interface is displaced upon heating by an amount given by

$$\Delta L = \left(\frac{\alpha_1 E_1 - \alpha_2 E_2}{E_1 + E_2}\right) L\,\Delta T,$$

where α_1, α_2 are the coefficients of linear expansion and E_1, E_2 are Young's moduli of the materials. Ignore changes in cross-sectional areas; see Fig. 19*b*. (*b*) Find the stress at the interface after heating.

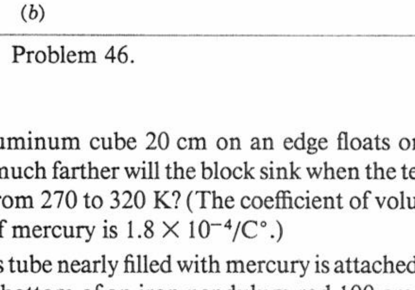

Figure 19 Problem 46.

47. An aluminum cube 20 cm on an edge floats on mercury. How much farther will the block sink when the temperature rises from 270 to 320 K? (The coefficient of volume expansion of mercury is 1.8×10^{-4}/C°.)

48. A glass tube nearly filled with mercury is attached in tandem to the bottom of an iron pendulum rod 100 cm long. How high must the mercury be in the glass tube so that the center of mass of this pendulum will not rise or fall with changes in temperature? (The cross-sectional area of the tube is equal to that of the iron rod. Neglect the mass of the glass. Iron has a density of 7.87×10^3 kg/m^3 and a coefficient of linear expansion equal to 12×10^{-6}/C°. The coefficient of volume expansion of mercury is 18×10^{-5}/C°.)

49. The distance between the towers of the main span of the Golden Gate Bridge near San Francisco is 4200 ft (Fig. 20). The sag of the cable halfway between the towers at 50°F is 470 ft. Take $\alpha = 6.5 \times 10^{-6}$/F° for the cable and compute (*a*) the change in length of the cable and (*b*) the change in sag for a temperature change from 10 to 90°F. Assume no bending or separation of the towers and a parabolic shape for the cable.

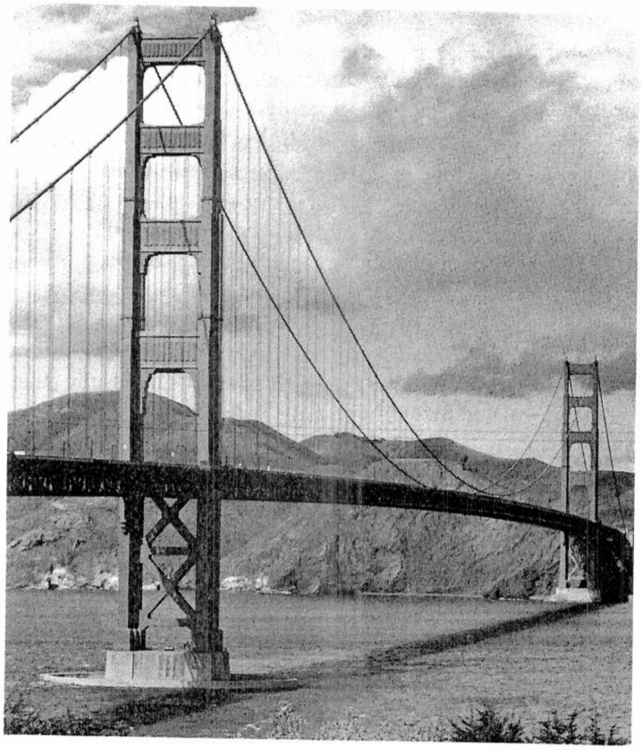

Figure 20 Problem 49.