of thermodynamics can be used to ascertain the sense of time independent of any frame of reference; that is, we shall take the positive direction of time to be that of statistically increasing disorder, or increasing entropy." (See, in this connection, "The Arrow of Time," by David Layzer, *Scientific American,* December 1975, p. 56.)

32. Explain the statement: "Cosmic rays continually *decrease* the entropy of the Earth on which they fall." Why does this not contradict the second law of thermodynamics?

33. When we put cards together in a deck or put bricks together to build a house, for example, we increase the order in the physical world. Does this violate the second law of thermodynamics? Explain.

34. Can one use terrestrial thermodynamics, which is known to apply to bounded and isolated bodies, for the whole universe? If so, is the universe bounded and from what is the universe isolated?

35. Temperature and pressure are examples of *intensive* properties of a system, their values for any sample of the system being independent of the size of the sample. However, entropy, like internal energy, is an *extensive* property, its value for any sample of a system being proportional to the size of the sample. Discuss.

36. The first, second, and third laws of thermodynamics may be paraphrased, respectively, as follows: (1) You can't win. (2) You can't even break even. (3) You can't get out of the game. Explain in what sense these are permissible restatements.

PROBLEMS

Section 26-2 Heat Engines and the Second Law

1. A heat engine absorbs 52.4 kJ of heat and exhausts 36.2 kJ of heat each cycle. Calculate (*a*) the efficiency and (*b*) the work done by the engine per cycle.

2. A car engine delivers 8.18 kJ of work per cycle. (*a*) Before a tuneup, the efficiency is 25.0%. Calculate, per cycle, the heat absorbed from the combustion of fuel and the heat exhausted to the atmosphere. (*b*) After a tuneup, the efficiency is 31.0%. What are the new values of the quantities calculated in (*a*)?

3. Calculate the efficiency of a fossil-fuel power plant that consumes 382 metric tons of coal each hour to produce useful work at the rate of 755 MW. The heat of combustion of coal is 28.0 MJ/kg.

4. Two moles of a monatomic ideal gas are caused to go through the cycle shown in Fig. 14. Process bc is a reversible adiabatic expansion. Also, $p_b = 10.4$ atm, $V_b = 1.22$ m^3, and $V_c = 9.13$ m^3. Calculate (*a*) the heat added to the gas, (*b*) the heat leaving the gas, (*c*) the net work done by the gas, and (*d*) the efficiency of the cycle.

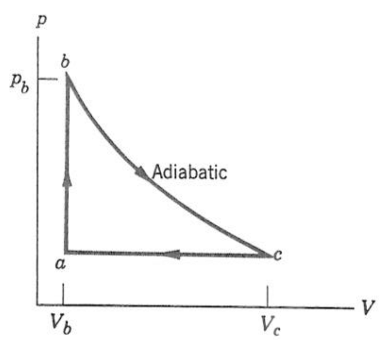

Figure 14 Problem 4.

5. One mole of a monatomic ideal gas initially at a volume of 10 L and a temperature 300 K is heated at constant volume to a temperature of 600 K, allowed to expand isothermally to its initial pressure, and finally compressed isobarically (that is, at constant pressure) to its original volume, pressure, and temperature. (*a*) Compute the heat input to the system during one cycle. (*b*) What is the net work done by the gas during one cycle? (*c*) What is the efficiency of this cycle?

6. A gasoline internal combustion engine can be approximated by the cycle shown in Fig. 15. Assume an ideal diatomic gas and use a compression ratio of 4 : 1 ($V_d = 4V_a$). Assume that $p_b = 3p_a$. (*a*) Determine the pressure and temperature of each of the vertex points of the pV diagram in terms of p_a and T_a. (*b*) Calculate the efficiency of the cycle.

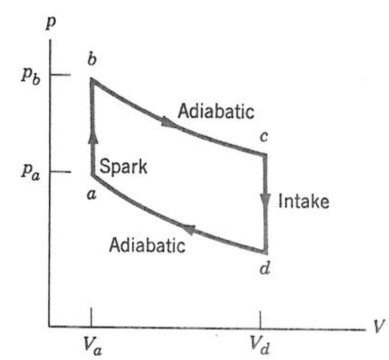

Figure 15 Problem 6.

Engine *A*, compared to engine *B*, produces, per cycle, five times the work but receives three times the heat input and exhausts twice the heat out. Determine the efficiency of each engine.

Section 26-3 Refrigerators and the Second Law

8. A refrigerator does 153 J of work to transfer 568 J of heat from its cold compartment. (*a*) Calculate the refrigerator's coefficient of performance. (*b*) How much heat is exhausted to the kitchen?

9. To make some ice, a freezer extracts 185 kJ of heat at $-12.0°$C. The freezer has a coefficient of performance of 5.70. The room temperature is 26.0°C. (*a*) How much heat was delivered to the room? (*b*) How much work was required to run the freezer?

Section 26-4 The Carnot Cycle

10. How much work must be done to extract 10.0 J of heat (*a*) from a reservoir at 7°C and transfer it to one at 27°C by means of a refrigerator using a Carnot cycle; (*b*) from one at −73°C to one at 27°C; (*c*) from one at −173°C to one at 27°C; and (*d*) from one at −223°C to one at 27°C?

11. In a Carnot cycle, the isothermal expansion of an ideal gas takes place at 412 K and the isothermal compression at 297 K. During the expansion, 2090 J of heat energy are transferred to the gas. Determine (*a*) the work performed by the gas during the isothermal expansion, (*b*) the heat rejected from the gas during the isothermal compression, and (*c*) the work done on the gas during the isothermal compression.

12. A Carnot engine has an efficiency of 22%. It operates between heat reservoirs differing in temperature by 75 C°. Find the temperatures of the reservoirs.

13. For the Carnot cycle illustrated in Fig. 7, show that the work done by the gas during process *bc* (step 2) has the same absolute value as the work done on the gas during process *da* (step 4).

14. Apparatus that liquifies helium is in a laboratory at 296 K. The helium in the apparatus is at 4.0 K. If 150 mJ of heat is transferred from the helium, find the minimum amount of heat delivered to the laboratory.

15. An air conditioner takes air from a room at 70°F and transfers it to the outdoors, which is at 95°F. For each joule of electrical energy required to run the refrigerator, how many joules of heat are transferred from the room?

16. An inventor claims to have created a heat pump that draws heat from a lake at 3.0°C and delivers heat at a rate of 20 kW to a building at 35°C, while using only 1.9 kW of electrical power. How would you judge the claim?

17. (*a*) A Carnot engine operates between a hot reservoir at 322 K and a cold reservoir at 258 K. If it absorbs 568 J of heat per cycle at the hot reservoir, how much work per cycle does it deliver? (*b*) If the same engine, working in reverse, functions as a refrigerator between the same two reservoirs, how much work per cycle must be supplied to transfer 1230 J of heat from the cold reservoir?

18. A heat pump is used to heat a building. The outside temperature is −5.0°C and the temperature inside the building is to be maintained at 22°C. The coefficient of performance is 3.8, and the pump delivers 7.6 MJ of heat to the building each hour. At what rate must work be done to run the pump?

19. If a Carnot cycle is run backward, we have an ideal refrigerator. A quantity of heat $|Q_L|$ is taken in at the lower temperature T_L and a quantity of heat $|Q_H|$ is given out at the higher temperature T_H. The difference is the work W that must be supplied to run the refrigerator. (*a*) Show that

$$|W| = |Q_L| \frac{T_H - T_L}{T_L}.$$

(*b*) The coefficient of performance K of a refrigerator is defined as the ratio of the heat extracted from the cold source to the work needed to run the refrigerator. Show that ideally

$$K = \frac{T_L}{T_H - T_L}.$$

(*c*) In a mechanical refrigerator the low-temperature coils are at a temperature of −13°C and the compressed gas in the condenser has a temperature of 25°C. Find the theoretical coefficient of performance.

20. The motor in a refrigerator has a power output of 210 W. The freezing compartment is at −3.0°C and the outside air is at 26°C. Assuming that the efficiency is 85% of the ideal, calculate the amount of heat that can be extracted from the freezing compartment in 15 min.

21. Show that the efficiency of a reversible ideal heat engine is related to the coefficient of performance of the reversible refrigerator obtained by running the engine backward by the relation $e = 1/(K+1)$.

22. (*a*) In a two-stage Carnot heat engine, a quantity of heat $|Q_1|$ is absorbed at a temperature T_1, work $|W_1|$ is done, and a quantity of heat $|Q_2|$ is expelled at a lower temperature T_2 by the first stage. The second stage absorbs the heat expelled by the first, does work $|W_2|$, and expels a quantity of heat $|Q_3|$ at a lower temperature T_3. Prove that the efficiency of the combination is $(T_1 - T_3)/T_1$. (*b*) A combination mercury–steam turbine takes saturated mercury vapor from a boiler at 469°C and exhausts it to heat a steam boiler at 238°C. The steam turbine receives steam at this temperature and exhausts it to a condenser at 37.8°C. Calculate the maximum efficiency of the combination.

23. A Carnot engine works between temperatures T_1 and T_2. It drives a Carnot refrigerator that works between two different temperatures T_3 and T_4 (see Fig. 16). Find the ratio $|Q_3|/|Q_1|$ in terms of the four temperatures.

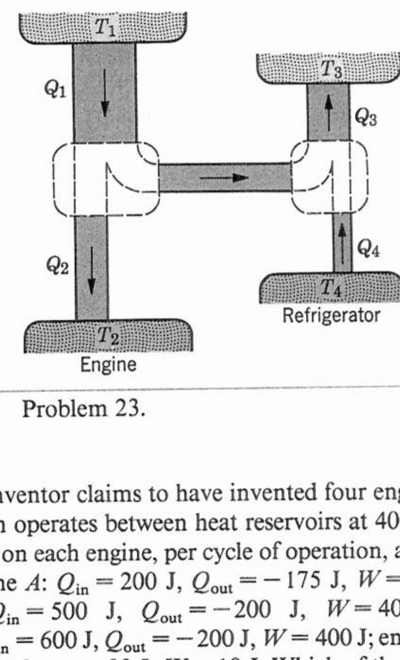

Figure 16 Problem 23.

24. An inventor claims to have invented four engines, each of which operates between heat reservoirs at 400 and 300 K. Data on each engine, per cycle of operation, are as follows: Engine *A*: $Q_{in} = 200$ J, $Q_{out} = -175$ J, $W = 40$ J; engine *B*: $Q_{in} = 500$ J, $Q_{out} = -200$ J, $W = 400$ J; engine *C*: $Q_{in} = 600$ J, $Q_{out} = -200$ J, $W = 400$ J; engine *D*: $Q_{in} = 100$ J, $Q_{out} = -90$ J, $W = 10$ J. Which of the first and second laws of thermodynamics (if either) does each engine violate?

25. In a steam locomotive, steam at a boiler pressure of 16.0 atm enters the cylinders, is expanded adiabatically to 5.60 times its original volume, and then exhausted to the atmosphere. Calculate (*a*) the steam pressure after expansion and (*b*) the greatest possible efficiency of the engine.

26. (*a*) Plot accurately a Carnot cycle on a pV diagram for 1.00

mol of an ideal gas. Let point a (see Fig. 7) correspond to $p = 1.00$ atm, $T = 300$ K, and let point b correspond to 0.500 atm, $T = 300$ K; take the low-temperature reservoir to be at 100 K. Let $\gamma = 1.67$. (*b*) Compute graphically the work done in this cycle. (*c*) Compute the work analytically.

27. One mole of an ideal monatomic gas is used as the working substance of an engine that operates on the cycle shown in Fig. 17. Calculate (*a*) the work done by the engine per cycle, (*b*) the heat added per cycle during the expansion stroke *abc*, and (*c*) the engine efficiency. (*d*) What is the Carnot efficiency of an engine operating between the highest and lowest temperatures present in the cycle? How does this compare to the efficiency calculated in (*c*)? Assume that $p_1 = 2p_0$, $V_1 = 2V_0$, $p_0 = 1.01 \times 10^5$ Pa, and $V_0 = 0.0225$ m^3.

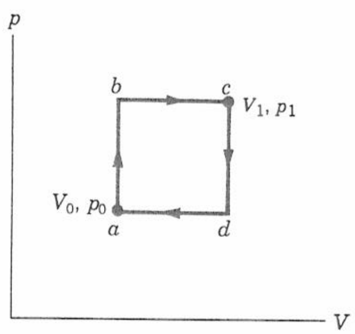

Figure 17 Problem 27.

Section 26-6 Entropy: Reversible Processes

28. In Fig. 12*c*, suppose that the change in entropy of the system in passing from state a to state b along path 1 is $+0.60$ J/K. What is the entropy change in passing (*a*) from state a to b along path 2 and (*b*) from state b to a along path 2?

29. An ideal gas undergoes a reversible isothermal expansion at 132°C. The entropy of the gas increases by 46.2 J/K. How much heat was absorbed?

30. Four moles of an ideal gas are caused to expand from a volume V_1 to a volume $V_2 = 3.45 V_1$. (*a*) If the expansion is isothermal at the temperature $T = 410$ K, find the work done on the expanding gas. (*b*) Find the change in entropy, if any. (*c*) If the expansion were reversibly adiabatic instead of isothermal, what is the entropy change?

31. (*a*) Show that a Carnot cycle, plotted on an absolute temperature versus entropy (*TS*) diagram, graphs as a rectangle.

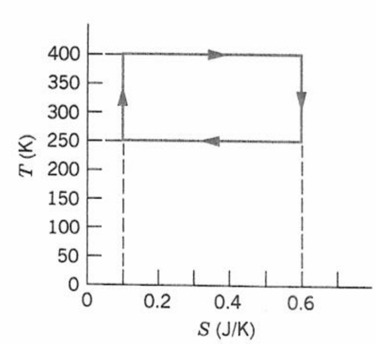

Figure 18 Problem 31.

For the Carnot cycle shown in Fig. 18, calculate (*b*) the heat that enters and (*c*) the work done on the system.

32. Find (*a*) the heat absorbed and (*b*) the change in entropy of a 1.22-kg block of copper whose temperature is increased reversibly from 25.0 to 105°C.

33. At very low temperatures, the molar specific heat of many solids is (approximately) proportional to T^3; that is, $C_V = AT^3$, where A depends on the particular substance. For aluminum, $A = 3.15 \times 10^{-5}$ J/mol·K^4. Find the entropy change of 4.8 mol of aluminum when its temperature is raised from 5.0 to 10 K.

34. Heat can be transferred from water at 0°C and atmospheric pressure without causing the water to freeze, if done with little disturbance of the water. Suppose the water is cooled to −5.0°C before ice begins to form. Find the change in entropy occurring during the sudden freezing of 1.0 g of water that then takes place.

35. An object of constant heat capacity C is heated from an initial temperature T_i to a final temperature T_f by being placed in contact with a reservoir at T_f. Represent the process on a graph of C/T versus T and show graphically that the total change in entropy ΔS (object plus reservoir) is positive and (*b*) show how the use of reservoirs at intermediate temperatures would allow the process to be carried out in a way that makes ΔS as small as desired.

36. One mole of an ideal monatomic gas is caused to go through the cycle shown in Fig. 19. (*a*) How much work is done on the gas in expanding the gas from a to c along path *abc*? (*b*) What is the change in internal energy and entropy in going from b to c? (*c*) What is the change in internal energy and entropy in going through one complete cycle? Express all answers in terms of the pressure p_0 and volume V_0 at point a in the diagram.

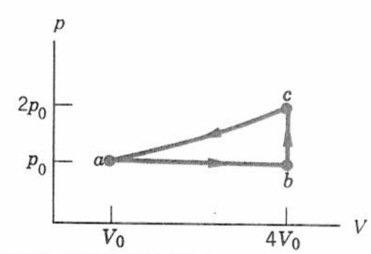

Figure 19 Problem 36.

Section 26-7 Entropy: Irreversible Processes

37. An ideal gas undergoes an isothermal expansion at 77°C, increasing its volume from 1.3 to 3.4 L. The entropy change of the gas is 24 J/K. How many moles of gas are present?

38. Suppose that the same amount of heat energy, say, 260 J, is transferred by conduction from a heat reservoir at a temperature of 400 K to another reservoir, the temperature of which is (*a*) 100 K, (*b*) 200 K, (*c*) 300 K, and (*d*) 360 K. Calculate the changes in entropy and discuss the trend.

39. A brass rod is in thermal contact with a heat reservoir at 130°C at one end and a heat reservoir at 24.0°C at the other end. (*a*) Compute the total change in the entropy arising from the process of conduction of 1200 J of heat through the rod. (*b*) Does the entropy of the rod change in the process?

40. One mole of an ideal diatomic gas is caused to pass through the cycle shown on the pV diagram in Fig. 20 where $V_2 = 3V_1$. Determine, in terms of p_1, V_1, T_1, and R: (*a*) p_2, p_3, and T_3 and (*b*) W, Q, ΔE_{int}, and ΔS for all three processes.

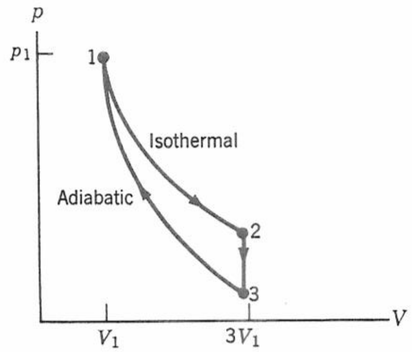

Figure 20 Problem 40.

41. One mole of a monatomic ideal gas is taken from an initial state of pressure p_0 and volume V_0 to a final state of pressure $2p_0$ and volume $2V_0$ by two different processes. (I) It expands isothermally until its volume is doubled, and then its pressure is increased at constant volume to the final state. (II) It is compressed isothermally until its pressure is doubled, and then its volume is increased at constant pressure to the final state. Show the path of each process on a pV diagram. For each process calculate in terms of p_0 and V_0: (*a*) the heat absorbed by the gas in each part of the process; (*b*) the work done on the gas in each part of the process; (*c*) the change in internal energy of the gas, $E_{int,f} - E_{int,i}$; and (*d*) the change in entropy of the gas, $S_f - S_i$.

Section 26-8 Entropy and the Second Law

42. A 50.0-g block of copper having a temperature of 400 K is placed in an insulating box with a 100-g block of lead having a temperature of 200 K. (*a*) What is the equilibrium temperature of this two-block system? (*b*) What is the change in the internal energy of the two-block system as it changes from the initial condition to the equilibrium condition? (*c*) What is the change in the entropy of the two-block system? (See Table 1 in Chapter 25.)

43. A mixture of 1.78 kg of water and 262 g of ice at 0°C is, in a reversible process, brought to a final equilibrium state where the water/ice ratio, by mass, is 1 : 1 at 0°C. (*a*) Calculate the entropy change of the system during this process. (*b*) The system is then returned to the first equilibrium state, but in an irreversible way (by using a Bunsen burner, for instance). Calculate the entropy change of the system during this process. (*c*) Show that your answer is consistent with the second law of thermodynamics.

44. In a specific heat experiment, 196 g of aluminum at 107°C is mixed with 52.3 g of water at 18.6°C. (*a*) Calculate the equilibrium temperature. Find the entropy change of (*b*) the aluminum and (*c*) the water. (*d*) Calculate the entropy change of the system. (*Hint*: See Eqs. 29 and 30.)

45. A 12.6-g ice cube at −10.0°C is placed in a lake whose temperature is +15.0°C. Calculate the change in entropy of the system as the ice cube comes to thermal equilibrium with the lake. (*Hint*: Will the ice cube affect the temperature of the lake?)