15

THE LAWS OF THERMODYNAMICS

Responses to Questions

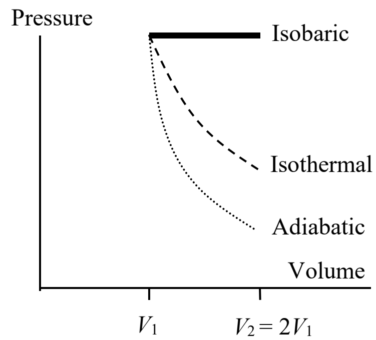
1. Since the process is isothermal, there is no change in the internal energy of the gas. Thus $\Delta U = Q - W = 0 \rightarrow Q = W$, so the heat absorbed by the gas is equal to the work done by the gas. Thus 3700 J of heat was added to the gas.

2. Mechanical energy can be transformed completely into heat. When a moving object slides across a rough level floor and eventually stops, the mechanical energy of the moving object has been transformed completely into heat. Also, if a moving object were to be used to compress a frictionless piston containing an insulated gas, the kinetic energy of the object would become internal energy of the gas. A gas that expands adiabatically (without heat transfer) transforms internal energy into mechanical energy, by doing work on its surroundings at the expense of its internal energy. Of course, that is an ideal (reversible) process. In any nonideal process, only a fraction of the internal energy can be changed into mechanical energy. Some of the internal energy might also be changed into heat.

3. It is possible for temperature (and thus internal energy) to remain constant in a system even though there is heat flow into or out of the system. By the first law of thermodynamics, there must be an equal amount of work done on or by the system, so that $\Delta U = Q - W = 0 \rightarrow Q = W$. The isothermal expansion or compression of a gas is an example of this situation. A change of state (melting, freezing, boiling, condensing, evaporating) is another example of heat transfer without a corresponding temperature change.

4. If the gas is compressed adiabatically, then no heat enters or leaves from the gas. The compression means that work was done ON the gas. By the first law of thermodynamics, $\Delta U = Q - W$, since $Q = 0$, then $\Delta U = 2W$. The change in internal energy is equal to the opposite of the work done by the gas or is equal to the work done on the gas. Since positive work was done on the gas, the internal energy of the gas increased, and that corresponds to an increase in temperature. This is conservation of energy—the work done on the gas becomes internal energy of the gas particles, and the temperature increases accordingly.

5. ΔU is proportional to the change in temperature. The change in the internal energy is zero for the isothermal process, greatest for the isobaric process, and least (negative) for the adiabatic process. The work done, W, is the area under the curve and is greatest for the isobaric process and least for the adiabatic process. From the first law of thermodynamics, Q is the sum of ΔU and W and is zero for the adiabatic process and a maximum for the isobaric process.



6. (*a*) When the lid is removed, the chlorine gas mixes with the air in the room around the bottle so that eventually both the room and the bottle contain a mixture of air and chlorine.
   (*b*) The reverse process, in which the individual chlorine particles reorganize so that they are all in the bottle, violates the second law of thermodynamics and does not occur naturally. It would require a spontaneous decrease in entropy.
   (*c*) Adding a drop of food coloring to a glass of water is another example of an irreversible process; the food coloring will eventually disperse throughout the water but will not ever gather into a drop again. The toppling of buildings during an earthquake is another example. The toppled building will not ever become "reconstructed" by another earthquake.

7. No. The definition of heat engine efficiency as $e = W/Q_L$ does not account for Q_H, the energy needed to produce the work. Efficiency should relate the input energy and the output work. This definition of efficiency is also not useful because if the exhaust heat Q_L is less than the work done W (which is possible), the "efficiency" would exceed unity.

8. (*a*) In an internal combustion engine, the high-temperature reservoir is the ignited gas–air mixture in the cylinder. The low-temperature reservoir is the "outside" air. The burned gases leave through the exhaust pipe.
   (*b*) In the steam engine, the high-temperature reservoir is the heated, high-pressure steam from the boiler. The low-temperature reservoir is the condensed water in the condenser.

   In the cases of both these engines, these areas are not technically heat "reservoirs," because each one is not at a constant temperature.

9. To utilize thermal energy from the ocean, a heat engine would need to be developed that operated between two different temperatures. If surface temperature water was to be both the source and the exhaust, then no work could be extracted. If the temperature difference between surface and deep ocean waters were to be used, then there would be considerable engineering obstacles, high expense, and potential environmental difficulties involved in having a heat engine that connected surface water and deep ocean water. Likewise, if the difference in temperature between tropical water and arctic water were to be used, then major difficulties would be involved because of the large distances involved.

10. It is possible to warm the kitchen in the winter by having the oven door open. The oven heating elements radiate heat energy into the oven cavity, and if the oven door is open, then the oven is just heating a bigger volume than usual. There is no thermodynamic cycle involved here. However, you cannot cool the kitchen by having the refrigerator door open. The refrigerator exhausts more heat than it removes from the refrigerated volume, so the room actually gets warmer with the refrigerator door open because of the work done by the refrigerator compressor. If you could have the refrigerator exhaust into some other room, then the refrigerator would be similar to an air conditioner, and it could

cool the kitchen, while heating up some other space. Or you could unplug the refrigerator and open the door. That would cool the room somewhat, but would heat up the contents of the refrigerator, which is probably not a desired outcome!

11. For a refrigerator, $\mathrm{COP} = Q_L/W$. That definition makes sense because we are interested in removing heat from the low-temperature reservoir (the interior of the refrigerator). The more heat that can be removed per amount of input work, the better (more efficient) the refrigerator is.

    For a heat pump, $\mathrm{COP} = Q_H/W$. The objective of the heat pump is to heat (deliver Q_H) rather than cool (remove Q_L). It is the heat delivered to the house that is important now. The more heat that can be delivered to the house per amount of input work, the better the heat pump is.

12. Any air conditioner-type heat engine will remove heat from the room (Q_L—the low-temperature input). Work (W) is input to the device to enable it to remove heat from the low-temperature region. By the second law of thermodynamics (conservation of energy), there must be a high-temperature exhaust heat Q_H which is larger than Q_L. Perhaps the inventor has come up with some clever method of having that exhaust heat move into a well-insulated heat "sink," like a container of water. But eventually the addition of that heat to the device will cause the device to become warmer than the room itself, and then heat will be transferred to the room. One very simple device that could do what is described in the question would be a fan blowing over a large block of ice. Heat from the room will enter the ice; cool air from near the surface of the ice will be blown by the fan. But after the ice melts, the fan motor would again heat the air.

13. Some processes that would obey the first law of thermodynamics but not the second, if they actually occurred, include:
    - a cup of tea warms itself by gaining thermal energy from the cooler air molecules around it;
    - a ball sitting on a soccer field gathers energy from its surroundings and begins to roll;
    - a bowl of popcorn placed in the refrigerator "un-pops" as it cools;
    - an empty perfume bottle is placed in a room containing perfume molecules, and all of the perfume molecules move into the bottle from various directions at the same time;
    - water on the sidewalk coalesces into droplets that are propelled upward and rise into the air;
    - a house gets warmer in the winter while the outdoors gets colder, due to heat moving from the outdoors to inside the house.

14. While the state of the papers has changed from disorder to order, they did not do so spontaneously. An outside source (you) caused the increase in order. You had to provide energy to do this (through your metabolic processes), and in doing so, your entropy increased more than the entropy of the papers decreased. The overall effect is that the entropy of the universe increased, satisfying the second law of thermodynamics.

15. The first statement, "You can't get something for nothing," is a whimsical way of saying that energy is conserved. For instance, one way to write the first law is $W = Q - \Delta U$. This says that work done by a system must have a source—either heat is input to the system or the internal energy of the system is lowered. It "costs" energy—either heat energy or internal energy—to get work done. Another way to say this is that no heat engine can be built which puts out more energy in the form of work than it extracts in the form of heat or internal energy.

The second statement, “You can’t even break even,” reflects the fact that a consequence of the second law is that there is no heat engine that is 100% efficient. Even though the first law is satisfied by an engine that takes in 100 J of heat and outputs 100 J of work, the second law says that that is impossible. If 100 J of heat were taken in, then less than 100 J of work will be output from the heat engine, even if it is an ideal heat engine. Some energy will be “lost” as exhaust energy.

16. (*a*) If a gas expands adiabatically, then $Q = 0$, so $\Delta S = 0$ by Eq. 15–8, $\Delta S = Q/T$.

    (*b*) If a gas expands isothermally, then there is no change in its internal energy, and the gas does work on its surroundings. Thus by the first law of thermodynamics, there must be heat flow into the gas, so $\Delta S > 0$—the entropy of the gas increases.

17. One kilogram of liquid iron will have greater entropy, since it is less ordered than solid iron and its molecules have more thermal motion. In addition, heat must be added to solid iron to melt it; the addition of heat will increase the entropy of the iron.

18. (*a*) The erosion of soil due to water flow over the ground.

    (*b*) The oxidation of various metals (copper, zinc, iron, etc.) when left exposed to the air.

    (*c*) Fallen leaves decaying in the woods.

    (*d*) A pile of compost decomposing.

    (*e*) A landslide.

    The reverse of these processes is not observed.

19. In an action movie, you might see a building or car changing from an exploded state to an unexploded state, or a bullet that was fired going backward into the gun and the gunpowder “unexploding.” In a movie with vehicle crashes, you might observe two collided vehicles separating from each other, becoming unwrecked as they separate, or someone “unwrite” something on a piece of paper—moving a pen over paper, taking away written marks as the pen moves.

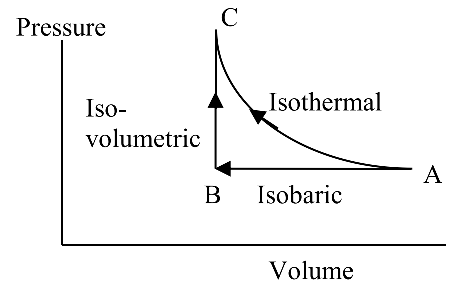
20. The synthesis of complex molecules from simple molecules does involve a decrease in entropy of the constituent molecules, since they have become more “structured” or “ordered.” However, the molecules are not a closed system. This process does not occur spontaneously or in isolation. The living organism in which the synthesis process occurs is part of the environment that must be considered for the overall change in entropy. The “living organism and environment” combination will have an increase in entropy that is larger than the decrease in entropy of the molecules, so overall, the second law is still satisfied, and the entropy of the entire system will increase.

Responses to MisConceptual Questions

1. (*d*) An isobaric process is one in which the pressure is kept constant. In a compression the volume of the gas decreases. By Eq. 15–3, the work done by the gas is negative, so an external force had to do work on the gas. In isobaric processes heat is allowed to flow into or out of the system and the internal energy changes.

2. (*c*) According to the second law of thermodynamics, it is impossible for heat to be entirely converted into work in a cycle or a heat engine. However, the question does not specify that we must consider a complete cycle. In an isothermal process $Q = W$. In an isothermal compression work is entirely converted into heat, and in an isothermal expansion heat is entirely converted into work.

3. (*c*) A common misconception is that the work done in moving an object between two states is independent of the path followed. In the graph shown, the work done in going from point A to B to C by the isobaric and isovolumetric processes is equal to the area under the AB line. The work done by the isothermal process is the area under the curved line. Since the AC line includes all of the area under the AB line as well as the area between the AB and AC lines, more work is done on the gas in the isothermal process.



4. (*d*) In an isothermal process the internal energy remains constant $(\Delta U = 0)$. In an expansion the gas does work on the surroundings $(W = 0)$. Since the internal energy is constant and the work is positive, the first law of thermodynamics requires the heat absorbed also be positive $(Q = 0)$.

5. (*d*) Students may misunderstand the difference between isothermal (temperature remains constant so $\Delta U = 0$) and adiabatic $(Q = 0)$. In an isothermal process heat can be absorbed, as long as an equal amount of work is done, so statement (i) is not true. For an ideal gas the temperature is proportional to the internal energy of the gas, statements (ii) and (iii) are equivalent, and both are true.

6. (*b*) As the gas expands, its volume increases and it does work on the surroundings. Since no heat is absorbed while the gas does this work, the first law of thermodynamics says that the internal energy and temperature of the gas must decrease. For the volume to increase as the temperature decreases, the ideal gas law requires that the pressure also decrease.

7. (*d*) A frequent misconception made in calculating the efficiency of an engine is to leave the temperatures in degrees Celsius, which would imply an efficiency of 50%. However, when the temperatures are properly converted to kelvins, Eq. 15–5 gives the efficiency as only about 34%.

8. (*d*) A common misconception in this situation is not realizing that a heat cycle running in reverse, like a refrigerator, must have a high-temperature exhaust. Furthermore, that high-temperature exhaust is the sum of the heat removed from the inside of the refrigerator and the work done by the refrigerator's compressor.

9. (*a, c*) The maximum efficiency of an engine is given by Eq. 15–5, which can be written in the form $e = (T_{\mathrm{H}} - T_{\mathrm{C}})/T_{\mathrm{H}}$. Increasing the temperature difference, as in (*a*), results in a higher efficiency. In (*b*) the temperature difference remains the same, while the hot temperature increases, which results in a lower efficiency. In (*c*) the efficiency increases as the temperature difference remains the same, but T_{H} decreases. In (*d*) the temperature difference decreases, which lowers the efficiency.

10. (*a*) The text states that "real engines that are well designed reach 60 to 80% of the Carnot efficiency." The cooling system of the engine keeps the high temperature at about 120°C (400 K) and the exhaust is about room temperature (300 K). The maximum efficiency would then be around 25%. Eighty percent of this maximum would be closest to 20% efficient. Any of the other choices for this question are not reasonable.

11. (*b*) Heat must be added to the ice cube to melt it. The change in entropy is the ratio of the heat added to the temperature of the ice cube. Since heat is absorbed in the process, the entropy increases.

Solutions to Problems

In solving these problems, the authors did not always follow the rules of significant figures rigidly. We tended to take quoted temperatures as correct to the number of digits shown, especially where other values might indicate that.

1. Use the first law of thermodynamics, Eq. 15–1, and the definition of internal energy, Eq. 14–1. Since the work is done by the gas, it is positive.

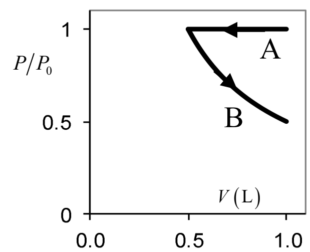
   (*a*) The temperature does not change, so $\boxed{\Delta U = 0}$.

   (b) $\Delta U = Q - W \rightarrow Q = \Delta U + W = 0 + 4.30\times 10^3\text{ J} = \boxed{4.30\times 10^3\text{ J}}$

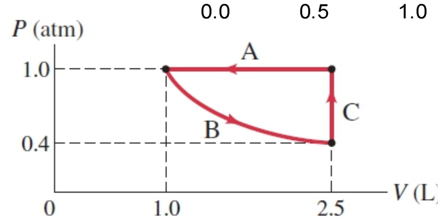
2. For the drawing of the graph, the pressure is given relative to the starting pressure, which is taken to be P_0.

   Segment A is the cooling at constant pressure.

   Segment B is the isothermal expansion.



3. Segment A is the compression at constant pressure. Since the process is at a constant pressure, the path on the diagram is horizontal from 2.5 L to 1.0 L.



   Segment B is the isothermal expansion. Since the temperature is constant, the ideal gas law says that the product PV is constant. Since the volume is increased by a factor of 2.5, the pressure must be divided by 2.5, so the final point on this segment is at a pressure of $1\text{ atm}/2.5 = 0.4\text{ atm}$. The path is a piece of a hyperbola.

   Segment C is the pressure increase at constant volume. Since the process is at a constant volume, the path on the diagram is vertical from 0.4 atm to 1.0 atm.

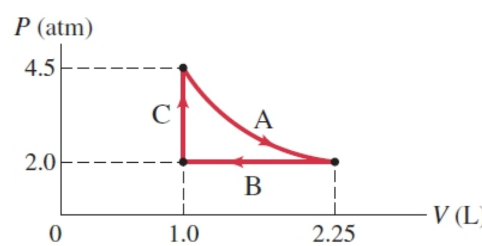
4. (*a*) The work done by a gas at constant pressure is found from Eq. 15–3.

   $$W = P\Delta V = (1\text{ atm})\left(\frac{1.01\times 10^5\text{ Pa}}{1\text{ atm}}\right)(16.2\text{ m}^3 - 12.0\text{ m}^3) = 4.242\times 10^5\text{ J} \approx \boxed{4.2\times 10^5\text{ J}}$$

   (*b*) The change in internal energy is calculated from the first law of thermodynamics.

   $$\Delta U = Q - W = (254\text{ kcal})\left(\frac{4186\text{ J}}{1\text{ kcal}}\right) - 4.242\times 10^5\text{ J} = \boxed{6.4\times 10^5\text{ J}}$$

5. The pressure must be converted to absolute pressure in order to use the ideal gas equation, so the initial pressure is 4.5 atm absolute pressure, and the lower pressure is 2.0 atm absolute pressure. Segment A is the isothermal expansion. The temperature and the amount of gas are constant, so $PV = nRT$ is constant. Since the pressure is reduced by a factor of 2.25, the volume increases by a factor of 2.25, to a final volume of 2.25 L. Segment B is the compression at constant pressure, and segment C is the pressure increase at constant volume.



6. (*a*) Since the container has rigid walls, there is no change in volume.

$$W = P\Delta V = \boxed{0}$$

(*b*) Use the first law of thermodynamics to find the change in internal energy.

$$\Delta U = Q - W = (-465\text{ kJ}) - 0 = \boxed{-465\text{ kJ}}$$

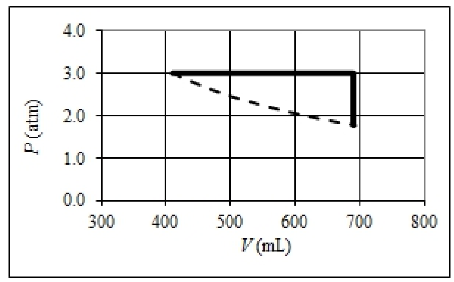
$\boxed{7.}$ (*a*) Since the process is adiabatic, $Q = \boxed{0}$.

(*b*) Use the first law of thermodynamics to find the change in internal energy.

$$\Delta U = Q - W = 0 - (-2630\text{ J}) = \boxed{2630\text{ J}}$$

(*c*) Since the internal energy is proportional to the temperature, a rise in internal energy means a $\boxed{\text{rise}}$ in temperature.

8. A graph of the process is shown. The expansion process is the horizontal line, and the constant-volume process is the vertical line. The dashed line is an isotherm starting from the original state.



(*a*) Work is only done in the expansion at constant pressure, since there must be a volume change in order for there to be work done.

$$W = P\Delta V$$

$$= (3.0\text{ atm})\left(\frac{1.01\times10^5\text{ Pa}}{1\text{ atm}}\right)(0.28\text{ L})\frac{1\times10^{-3}\text{ m}^3}{1\text{ L}} = \boxed{85\text{ J}}$$

(*b*) Use the first law of thermodynamics to find the heat flow. Notice that the temperature change over the entire process is 0, so there is no change in internal energy.

$$\Delta U = Q - W = 0 \quad\rightarrow\quad Q = W = \boxed{85\text{ J}}$$

9. Since the expansion is adiabatic, there is no heat flow into or out of the gas. Use the first law of thermodynamics to calculate the temperature change.

$$\Delta U = Q - W \quad\rightarrow\quad \tfrac{3}{2}nR\Delta T = 0 - W \quad\rightarrow$$

$$\Delta T = -\tfrac{2}{3}\frac{W}{nR} = -\frac{2(8300\text{ J})}{3(8.5\text{ mol})(8.314\text{ J/mol}\cdot\text{K})} = -78.3\text{ K} \approx \boxed{-78\text{ K}}$$

10. (*a*) No work is done during the first step, since the volume is constant. The work in the second step is given by $W = P\Delta V$.

$$W = P\Delta V = (1.4\text{ atm})\left(\frac{1.01\times10^5\text{ Pa}}{1\text{ atm}}\right)(9.3\text{ L} - 5.9\text{ L})\left(\frac{1\times10^{23}\text{ m}^3}{1\text{ L}}\right) = \boxed{480\text{ J}}$$

(*b*) Since there is no overall change in temperature, $\Delta U = \boxed{0}$.

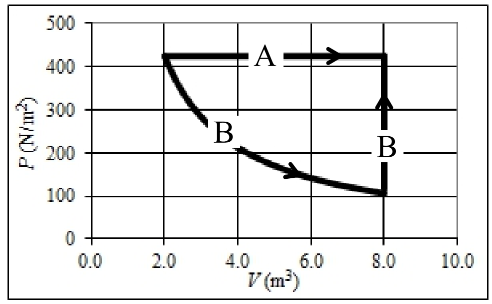
(*c*) The heat flow can be found from the first law of thermodynamics.

$$\Delta U = Q - W \rightarrow Q = \Delta U + W = 0 + 480\text{ J} = \boxed{480\text{ J (into the gas)}}$$

11. (*a*) Since the gas is well insulated, no heat can flow into or out of the gas. When the gas is compressed, work is done on that gas. Thus the gas gains energy. That energy manifests as an increase in the average kinetic energy of the gas particles, so the temperature of the gas increases.

    (*b*) When the gas expands, the opposite effect occurs. The gas does work on the piston during the expansion. To accomplish that work, the energy of the gas decreases. Since the gas is well insulated, no heat can flow into the gas to compensate for that lost work, so the average kinetic energy of the gas particles decreases, and thus there is a decrease in temperature.

12. (a) See the diagram. The isobaric expansion is just a horizontal line on the graph.



    (*b*) The work done is found from Eq. 15–3.

$$W = P\Delta V$$
$$= (425\ \text{N/m}^2)(8.00\ \text{m}^3 - 2.00\ \text{m}^3) = \boxed{2550\ \text{J}}$$

The change in internal energy depends on the temperature change, which can be related to the ideal gas law, $PV = nRT$.

$$\Delta U = \tfrac{3}{2}nR\Delta T = \tfrac{3}{2}(nRT_2 - nRT_1)$$
$$= \tfrac{3}{2}[(PV)_2 - (PV)_1] = \tfrac{3}{2}P\Delta V = \tfrac{3}{2}W = \tfrac{3}{2}(2550\ \text{J}) = \boxed{3830\ \text{J}}$$

    (*c*) For the isothermal expansion, since the volume expands by a factor of 4, the pressure drops by a factor of 4 to $106\ \text{N/m}^2$. See the diagram.

    (*d*) The change in internal energy only depends on the initial and final temperatures. Since those temperatures are the same for process B as they are for process A, the internal energy change is the same for process B as for process A, $\boxed{3830\ \text{J}}$.

13. For the path ac, use the first law of thermodynamics to find the change in internal energy.

$$\Delta U_{\text{ac}} = Q_{\text{ac}} - W_{\text{ac}} = -63\ \text{J} - (-35\ \text{J}) = -28\ \text{J}$$

Since internal energy only depends on the initial and final temperatures, this $\overset{\rightarrow}{\Delta U}$ applies to any path that starts at a and ends at c. And for any path that starts at c and ends at a, $\Delta U_{\text{ca}} = 2\,\Delta U_{\text{ac}} = 28$ J.

    (*a*) Use the first law of thermodynamics to find Q_{abc}.

$$\Delta U_{\text{abc}} = Q_{\text{abc}} - W_{\text{abc}} \quad \rightarrow \quad Q_{\text{abc}} = \Delta U_{\text{abc}} + W_{\text{abc}} = -28\ \text{J} + (-54\ \text{J}) = \boxed{-82\ \text{J}}$$

    (*b*) Since the work along path bc is 0, $W_{\text{abc}} = W_{\text{ab}} = P_{\text{b}}\Delta V_{\text{ab}} = P_{\text{b}}(V_{\text{b}} - V_{\text{a}})$. Also note that the work along path da is 0.

$$W_{\text{cda}} = W_{\text{cd}} = P_{\text{c}}\Delta V_{\text{cd}} = P_{\text{c}}(V_{\text{d}} - V_{\text{c}}) = \tfrac{1}{2}P_{\text{b}}(V_{\text{a}} - V_{\text{b}}) = -\tfrac{1}{2}W_{\text{abc}} = -\tfrac{1}{2}(-54\ \text{J}) = \boxed{27\ \text{J}}$$

    (*c*) Use the first law of thermodynamics to find Q_{abc}.

$$\Delta U_{\text{cda}} = Q_{\text{cda}} - W_{\text{cda}} \quad \rightarrow \quad Q_{\text{cda}} = \Delta U_{\text{cda}} + W_{\text{cda}} = 28\ \text{J} + 27\ \text{J} = \boxed{55\ \text{J}}$$

    (*d*) As found above, $U_{\text{c}} - U_{\text{a}} = \Delta U_{\text{ca}} = -\Delta U_{\text{ac}} = \boxed{28\ \text{J}}$.

(*e*) $U_{\text{d}} - U_{\text{c}} = 12\text{ J} \rightarrow U_{\text{d}} = U_{\text{c}} + 12\text{ J} \rightarrow$

$$\Delta U_{\text{da}} = U_{\text{a}} - U_{\text{d}} = U_{\text{a}} - U_{\text{c}} - 12\text{ J} = \Delta U_{\text{ca}} - 12\text{ J} = 28\text{ J} - 12\text{ J} = 16\text{ J}$$

Use the first law of thermodynamics to find Q_{da}.

$$\Delta U_{\text{da}} = Q_{\text{da}} - W_{\text{da}} \rightarrow Q_{\text{da}} = \Delta U_{\text{da}} + W_{\text{da}} = 16\text{ J} + 0 = \boxed{16\text{ J}}$$

14. In Example 15–7, the total energy transformed was 1.15×10^{7} J. We will subtract the energy for 1 hour of desk work and add the energy for 1 hour of running.

$$\text{Energy} = 1.15\times10^{7}\text{ J} + [-115\text{ J/s} + 1150\text{ J/s}](3600\text{ s/h}) = \boxed{1.52\times10^{7}\text{ J}} \approx 3640\text{ Cal}$$

15. Follow the pattern set in Example 15–7. Find the average rate by dividing the total energy for the day by 24 hours.

$$\text{Avg. energy} = \begin{bmatrix}(8.0\text{ h})(70\text{ J/s}) + (6.0\text{ h})(115\text{ J/s}) + (6.0\text{ h})(230\text{ J/s}) \\ +(2.0\text{ h})(115\text{ J/s}) + (1.5\text{ h})(460\text{ J/s}) + (0.5\text{ h})(1150\text{ J/s})\end{bmatrix} \Big/ 24\text{ h} = 172\text{ W} \approx \boxed{170\text{ W}}$$

16. From Table 15–2, the change in metabolic rate if one hour of sleeping is exchanged for light activity is an addition of $230\text{ watts} - 70\text{ watts} = 160\text{ watts}$. Note that this increased rate is only applicable for one hour per day.

$$\left(160\frac{\text{J}}{\text{s}}\right)\left(\frac{3600\text{ s}}{1\text{ h}}\right)\left(\frac{1\text{ h}}{\text{day}}\right)\left(\frac{365\text{ day}}{1\text{ y}}\right)\left(\frac{1\text{ kg fat}}{4\times10^{7}\text{ J}}\right) = 5.256\text{ kg} \approx \boxed{5.3\text{ kg}}\left(\frac{2.20\text{ lb}}{1\text{ kg}}\right) = \boxed{12\text{ lb}}$$

17. (*a*) The person runs seven times per week, 30 minutes each time. We use Table 15–2.

$$\left(1150\frac{\text{J}}{\text{s}}\right)\left(\frac{60\text{ s}}{1\text{ min}}\right)\left(\frac{30\text{ min}}{\text{run}}\right)\left(\frac{7\text{ runs}}{1\text{ week}}\right) = 1.449\times10^{7}\text{ J/week} \approx \boxed{1.4\times10^{7}\text{ J}}\text{ in one week}$$

(*b*) Convert the energy used to run from joules to Calories.

$$1.449\times10^{7}\text{ J}\left(\frac{1\text{ Cal}}{4.186\times10^{3}\text{ J}}\right) = 3462\text{ Cal} \approx \boxed{3500\text{ Cal}}$$

18. The efficiency of a heat engine is given by Eq. 15–4a.

$$e = \frac{W}{Q_{\text{H}}} = \frac{W}{W + Q_{\text{L}}} = \frac{2600\text{ J}}{2600\text{ J} + 8200\text{ J}} = 0.24 = \boxed{24\%}$$

19. The maximum (or Carnot) efficiency is given by Eq. 15–5, with temperatures in kelvins.

$$e = 1 - \frac{T_{\text{L}}}{T_{\text{H}}} = 1 - \frac{(345 + 273)\text{ K}}{(560 + 273)\text{ K}} = 0.258 = \boxed{25.8\%}$$

We assume that both temperatures are measured to the same precision—the nearest degree.

$\boxed{20.}$ The Carnot efficiency is given by Eq. 15–5, with temperatures in kelvins.

$$e = 1 - \frac{T_{\text{L}}}{T_{\text{H}}} \rightarrow T_{\text{H}} = \frac{T_{\text{L}}}{1 - e} = \frac{(230 + 273)\text{ K}}{1 - 0.34} = 762\text{ K} = 489°\text{C} \approx \boxed{490°\text{C}}$$

21. The efficiency of a heat engine is given by Eq. 15–4a.

$$e = \frac{W}{Q_H} = \frac{9200\text{ J}}{(25.0\text{ kcal})(4186\text{ J/kcal})} = 0.0879 \approx \boxed{8.8\,\%}$$

22. Calculate the Carnot efficiency for the given temperatures, using Eq. 15–5.

$$e_{\text{ideal}} = 1 - \frac{T_L}{T_H} = 1 - \frac{77\text{ K}}{293\text{ K}} = 0.7372 \approx \boxed{74\%}$$

23. A 10°C decrease in the low-temperature reservoir will give a greater improvement in the efficiency of a Carnot engine. By definition, T_L is less than T_H, so a 10°C change will be a larger percentage change in T_L than in T_H, yielding a greater improvement in efficiency. As an example, we use the values from Problem 22 above.

$$e_{\substack{\text{lower}\\ T_L}} = 1 - \frac{T_L}{T_H} = 1 - \frac{67\text{ K}}{293\text{ K}} = 0.7713 \text{ compared to } 0.7372$$

$$e_{\substack{\text{higher}\\ T_H}} = 1 - \frac{T_L}{T_H} = 1 - \frac{77\text{ K}}{303\text{ K}} = 0.7458 \text{ compared to } 0.7372$$

We see that the decrease in the lower temperature was more effective. Here is a more rigorous proof. Note that we never multiply by a negative value, so the original ordering of $e_{\substack{\text{lower}\\ T_L}}$ on the left of the comparison and $e_{\substack{\text{higher}\\ T_H}}$ on the right of the comparison is preserved. We use the sign $<=>$ to mean "compare to."

$$e_{\substack{\text{lower}\\ T_L}} = 1 - \frac{T_L - T_0}{T_H}; \quad e_{\substack{\text{higher}\\ T_H}} = 1 - \frac{T_L}{T_H + T_0}$$

$$1 - \frac{T_L - T_0}{T_H} <=> 1 - \frac{T_L}{T_H + T_0}; \quad -\frac{T_L - T_0}{T_H} <=> -\frac{T_L}{T_H + T_0}; \quad \frac{T_L}{T_H + T_0} <=> \frac{T_L - T_0}{T_H};$$

$$T_L T_H <=> (T_L - T_0)(T_H + T_0); \quad T_0 T_H + T_0 T_0 <=> T_L T_0; \quad T_H + T_0 <=> T_L$$

Since the left-hand side of this last expression is larger than the right-hand side, $e_{\substack{\text{lower}\\ T_L}} > e_{\substack{\text{higher}\\ T_H}}$. Thus in general, $\boxed{\text{a change in the low-temperature reservoir has a larger effect}}$ on the efficiency than the same change in the high-temperature reservoir.

24. The efficiency of a heat engine is given by Eq. 15–4a.

$$e = \frac{W}{Q_H} = \frac{W}{W + Q_L} \quad \rightarrow \quad Q_L = W(1/e - 1) \quad \rightarrow$$

$$Q_L/t = W/t(1/e - 1) = (580\text{ MW})(1/0.32 - 1) = 1232\text{ MW} \approx \boxed{1200\text{ MW}}$$

25. The maximum (or Carnot) efficiency is given by Eq. 15–5, with temperatures in kelvins.

$$e = 1 - \frac{T_L}{T_H} = 1 - \frac{(330 + 273)\text{ K}}{(660 + 273)\text{ K}} = 0.3537$$

Thus the total power generated can be found as follows.

$$\text{Actual power} = (\text{Total power})(\text{max. eff.})(\text{operating eff.}) \quad \rightarrow$$

$$\text{Total power} = \frac{\text{Actual power}}{(\text{max. eff.})(\text{operating eff.})} = \frac{1.4\text{ GW}}{(0.3537)(0.65)} = 6.089\text{ GW}$$

$$\text{Exhaust power} = \text{Total power} - \text{Actual power} = 6.089\text{ GW} - 1.4\text{ GW} = 4.689\text{ GW}$$

$$= (4.689\times 10^9\text{ J/s})(3600\text{ s/h}) = 1.688\times 10^{13}\text{ J/h} \approx \boxed{1.7\times 10^{13}\text{ J/h}}$$

26. Find the intake temperature from the original Carnot efficiency, and then recalculate the exhaust temperature for the new Carnot efficiency, using the same intake temperature.

$$e_1 = 1 - \frac{T_{L1}}{T_H} \rightarrow T_H = \frac{T_{L1}}{1-e_1} = \frac{(340+273)\text{ K}}{1-0.36} = 958\text{ K}$$

$$e_2 = 1 - \frac{T_{L2}}{T_H} \rightarrow T_{L2} = T_H(1-e_2) = (958\text{ K})(1-0.42) = 556\text{ K} = 283^\circ\text{C} \approx \boxed{280^\circ\text{C}}$$

27. This is a perfect Carnot engine, so its efficiency is given by Eqs. 15–4a and 15–5. Use these two expressions to solve for the rate of heat output.

$$e = 1 - \frac{T_L}{T_H} = 1 - \frac{(45+273)\text{K}}{(210+273)\text{K}} = 0.3416 \quad e = \frac{W}{Q_H} = \frac{W}{W+Q_L} \rightarrow Q_L = W(1/e-1)$$

$$Q_L/t = W/t(1/e-1) = (910\text{ W})(1/0.3416-1) = 1754\text{ W} \approx \boxed{1800\text{ W}}$$

28. Find the exhaust temperature from the original Carnot efficiency, and then recalculate the intake temperature for the new Carnot efficiency, using the same exhaust temperature. Use Eq. 15–5.

$$e_1 = 1 - T_L/T_{H1} \rightarrow T_L = T_{H1}(1-e) = [(580+273)\text{ K}](1-0.22) = 665.3\text{ K}$$

$$e_2 = 1 - T_L/T_{H2} \rightarrow T_{H2} = \frac{T_L}{1-e_2} = \frac{665.3\text{ K}}{1-0.42} = 1147\text{ K} = 874^\circ\text{C} \approx \boxed{870^\circ\text{C}}$$

29. We calculate both the energy per second (power) delivered by the gasoline and the energy per second (power) needed to overcome the drag forces. The ratio of these is the efficiency, as given by Eq. 15–4a.

$$\frac{W}{t} = P_{\substack{\text{output}\\ \text{(to move}\\ \text{car)}}} = Fv = (350\text{ N})\left(55\frac{\text{mi}}{\text{h}}\right)\left(\frac{1609\text{ m}}{1\text{ mi}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 8604\text{ W}$$

$$\frac{Q_H}{t} = P_{\substack{\text{input}\\ \text{(from}\\ \text{gasoline)}}} = \left(3.2\times 10^7\frac{\text{J}}{\text{L}}\right)\left(\frac{3.8\text{ L}}{1\text{ gal}}\right)\left(\frac{1\text{ gal}}{32\text{ mi}}\right)\left(55\frac{\text{mi}}{\text{h}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 58056\text{ W}$$

$$e = \frac{W}{Q_H} = \frac{P_{\substack{\text{output}\\ \text{(to move}\\ \text{car)}}}}{P_{\substack{\text{input}\\ \text{(from}\\ \text{gasoline)}}}} = \frac{8604\text{ W}}{58056\text{ W}} = 0.148 \approx \boxed{0.15}$$

30. The ideal coefficient of performance is given by Eq. 15–6c.

$$\text{COP}_{\text{ideal}} = \frac{T_L}{T_H - T_L} = \frac{(273+2.5)\text{ K}}{(22-2.5)\text{ K}} = 14.13 \approx \boxed{14}$$

31. The coefficient of performance for a refrigerator is given by Eq. 15–6c, using absolute temperatures.

$$\text{COP} = \frac{T_L}{T_H - T_L} = \frac{(-8+273)\text{ K}}{(33+273)\text{ K} - (-8+273)\text{ K}} = 6.463 \approx \boxed{6.5}$$

32. The coefficient of performance for a refrigerator is given by Eq. 15–6c, using absolute temperatures.

$$\text{COP} = \frac{T_L}{T_H - T_L} \quad \rightarrow \quad T_L = T_H\left(\frac{\text{COP}}{1+\text{COP}}\right) = [(22+273)\text{ K}]\left(\frac{7.0}{8.0}\right) = 258.1\text{ K} = -14.9^\circ\text{C} \approx \boxed{-15^\circ\text{C}}$$

33. We initially assume a COP of 3.0. For a heat pump the COP is given by Eq. 15–7.

(*a*) $$\text{COP} = \frac{Q_H}{W} \quad \rightarrow \quad W = \frac{Q_H}{\text{COP}} = \frac{3100\text{ J}}{3.0} = 1033\text{ J} \approx \boxed{1.0\times10^3\text{ J}}$$

(*b*) The calculation doesn't depend on the outdoor temperature, so $W = \boxed{1.0\times10^3\text{ J}}$.

(*c*) The efficiency of a perfect Carnot engine is given by Eqs. 15–4a and 15–5. Equate these two expressions to solve for the work required.

$$e = 1 - \frac{T_L}{T_H}; \quad e = \frac{W}{Q_H} \quad \rightarrow \quad 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} \quad \rightarrow \quad W = Q_H\left(1 - \frac{T_L}{T_H}\right)$$

$$W = Q_H\left(1 - \frac{T_L}{T_H}\right) = 3100\text{ J}\left(1 - \frac{0+273}{22+273}\right) = \boxed{230\text{ J}}$$

$$W = Q_H\left(1 - \frac{T_L}{T_H}\right) = 3100\text{ J}\left(1 - \frac{-15+273}{22+273}\right) = \boxed{390\text{ J}}$$

34. The COP for an ideal heat pump is given by Eq. 15–7.

(*a*) $$\text{COP} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L} = \frac{(24+273)\text{ K}}{18\text{ K}} = 16.5 \approx \boxed{17}$$

(*b*) $$\text{COP} = \frac{Q_H}{W} \quad \rightarrow \quad Q_H = (W/t)(t)(\text{COP}) = (1200\text{ W})(3600\text{ s})(16.5) = 7.128\times10^7\text{ J} \approx \boxed{7.1\times10^7\text{ J}}$$

35. The \$2000 worth of heat provided by the electric heater is the same amount of heat that the heat pump would need to provide, so this Q_H costs \$2,000. The amount of energy required to run the heat pump to deliver that same amount of heat is found from the coefficient of performance.

$$\text{COP} = \frac{Q_H}{W} \quad \rightarrow \quad W = \frac{Q_H}{\text{COP}} = \frac{Q_H}{2.9}$$

So if the cost for Q_H is divided by 2.9, we get the cost of running the heat pump to deliver the needed heat. Subtract that from the total cost to get the savings.

$$\text{Savings} = \$2{,}000 - \frac{\$2{,}000}{2.9} \approx \boxed{\$1310}$$

Divide the cost of the heat pump by the annual savings to find the break-even time.

$$\frac{\$15{,}000}{\$1310/\text{year}} = 11.45\text{ years} \approx \boxed{11\text{ years}}$$

The total savings over 20 years is the savings in heating costs minus the price of the heat pump.

$$\text{Total savings} = (\$1310/\text{year})(20\text{ years}) - \$15{,}000 = \$11{,}200 \approx \boxed{\$11{,}000}$$

36. Heat energy is taken away from the water, so the change in entropy will be negative. The heat transfer is the mass of the steam times the latent heat of vaporization.

$$\Delta S = \frac{Q}{T} = -\frac{mL_{\text{V}}}{T} = -\frac{(0.320\text{ kg})(22.6\times 10^5\text{ J/kg})}{(273+100)\text{ K}} = -1939\text{ J/K} \approx \boxed{-1900\text{ J/K}}$$

37. The heat added to the water is found from Eq. 14–2, $\Delta Q = mc\Delta T$. Use the average temperature of $50°\text{C}$ in Eq. 15–8 for entropy.

$$\Delta S = \frac{Q}{T} = \frac{mc\Delta T}{T} = \frac{(1.0\text{ kg})(4186\text{ J/kg}\cdot\text{C}°)(100\text{ C}°)}{(273+50)\text{ K}} = 1296\text{ J/K} \approx \boxed{1300\text{ J/K}}$$

38. Energy has been made "unavailable" in the frictional stopping of the sliding box. We take that "lost" kinetic energy as the heat term of the entropy calculation, Eq. 15–8.

$$\Delta S = \frac{Q}{T} = \frac{\frac{1}{2}mv_0^2}{T} = \frac{\frac{1}{2}(5.8\text{ kg})(4.0\text{ m/s})^2}{293\text{ K}} = 0.1584\text{ J/K} \approx \boxed{0.16\text{ J/K}}$$

Since this is a decrease in "availability," the entropy of the universe has increased.

39. There are three terms of entropy to consider. First, there is a loss of entropy from the water for the freezing process, ΔS_1. Second, there is a loss of entropy from that newly formed ice as it cools to $-8.0°\text{C}$, ΔS_2. That process has an "average" temperature of $-4.0°\text{C}$. Finally, there is a gain of entropy by the "great deal of ice," ΔS_3, as the heat lost from the original mass of water in steps 1 and 2 goes into that great deal of ice. Since it is a large quantity of ice, we assume that its temperature does not change during the processes. The density of water is 1000 kg per cubic meter.

$$\Delta S_1 = \frac{Q_1}{T_1} = 2\,\frac{mL_{\text{F}}}{T_1} = -\frac{(1.00\times 10^3\text{ kg})(3.33\times 10^5\text{ J/kg})}{273\text{ K}} = -1.2198\times 10^6\text{ J/K}$$

$$\Delta S_2 = \frac{Q_2}{T_2} = -\frac{mc_{\text{ice}}\Delta T_2}{T_2} = -\frac{(1.00\times 10^3\text{ kg})(2100\text{ J/kg}\cdot\text{C}°)(8.0\text{ C}°)}{(-4+273)\text{ K}} = 2\,6.2453\times 10^4\text{ J/K}$$

$$\Delta S_3 = \frac{Q_3}{T_3} = \frac{-Q_1 - Q_2}{T_3} = \frac{mL_{\text{F}} + mc_{\text{ice}}\Delta T_2}{T_3}$$

$$= \frac{(1.00\times 10^3\text{ kg})[(3.33\times 10^5\text{ J/kg}) + (2100\text{ J/kg}\cdot\text{C}°)(8\text{ C}°)]}{(-8+273)\text{ K}} = 1.32\times 10^6\text{ J/K}$$

$\boxed{40.}$ The same amount of heat that leaves the high-temperature heat source enters the low-temperature body of water.

$$\Delta S = \Delta S_1 + \Delta S_2 = -\frac{Q}{T_{\text{high}}} + \frac{Q}{T_{\text{low}}} = Q\left(\frac{1}{T_{\text{low}}} - \frac{1}{T_{\text{high}}}\right) \rightarrow$$

$$\frac{\Delta S}{t} = \frac{Q}{t}\left(\frac{1}{T_{\text{low}}} - \frac{1}{T_{\text{high}}}\right) = (8.40\text{ cal/s})\left(\frac{4.186\text{ J}}{1\text{ cal}}\right)\left(\frac{1}{(22+273)\text{ K}} - \frac{1}{(225+273)\text{ K}}\right)$$

$$= \boxed{4.86\times 10^{-2}\,\frac{\text{J/K}}{\text{s}}}$$

41. Take the energy transfer to use as the initial kinetic energy of the rock, because this energy becomes "unusable" after the collision—it is transferred to the environment. We assume that the rock and the environment are both at temperature T_0.

$$\Delta S = Q/T \quad \rightarrow \quad \boxed{\Delta S = \text{KE}/T_0}$$

42. The same amount of heat that leaves the high-temperature water will enter the low-temperature water. Since the two masses of water are the same, the equilibrium temperature will be the midpoint between the two initial temperatures, $40°\text{C}$. The average temperature of the cool water is $(35°\text{C}+40°\text{C})/2 = 37.5°\text{C}$, and the average temperature of the warm water is $(45°\text{C}+40°\text{C})/2 = 42.5°\text{C}$.

$$\Delta S = \Delta S_1 + \Delta S_2 = 2\ \frac{Q}{T_{\text{high}}} + \frac{Q}{T_{\text{low}}} = mc\Delta T\left(\frac{1}{T_{\text{low}}} - \frac{1}{T_{\text{high}}}\right)$$

$$= (1.0\text{ kg})(4186\text{ J/kg}\cdot\text{C°})(5\text{ C°})\left(\frac{1}{(37.5+273)\text{ K}} - \frac{1}{(42.5+273)\text{ K}}\right) = 1.068\text{ J/K} \approx \boxed{1.1\text{ J/K}}$$

43. (*a*) $e_{\text{actual}} = W/Q_{\text{H}} = 550\text{ J}/2500\text{ J} = 0.22;\quad e_{\text{ideal}} = 1 - T_{\text{L}}/T_{\text{H}} = 1 - 650\text{ K}/970\text{ K} = 0.330$

Thus $e_{\text{actual}}/e_{\text{ideal}} = 0.220/0.330 = 0.667 \approx \boxed{67\text{ , of ideal}}$.

(*b*) The heat reservoirs do not change temperature during the operation of the engine. There is an entropy loss from the input reservoir, because it loses heat, and an entropy gain for the output reservoir, because it gains heat. Note that $Q_{\text{L}} = Q_{\text{H}} - W = 2500\text{ J} - 550\text{ J} = 1950\text{ J}$.

$$\Delta S = \Delta S_{\text{input}} + \Delta S_{\text{output}} = -\frac{Q_{\text{H}}}{T_{\text{H}}} + \frac{Q_{\text{L}}}{T_{\text{L}}} = -\frac{2500\text{ J}}{970\text{ K}} + \frac{1950\text{ J}}{650\text{ K}} = \boxed{0\ 42\text{ J/K}}$$

(*c*) For the Carnot engine, the exhaust energy will be $Q_{\text{L}} = Q_{\text{H}}(1 - e_{\text{Carnot}}) = Q_{\text{H}}T_{\text{L}}/T_{\text{H}}$.

$$\Delta S = \Delta S_{\text{input}} + \Delta S_{\text{output}} = -\frac{Q_{\text{H}}}{T_{\text{H}}} + \frac{Q_{\text{L}}}{T_{\text{L}}} = -\frac{Q_{\text{H}}}{T_{\text{H}}} + \frac{Q_{\text{H}}T_{\text{L}}/T_{\text{H}}}{T_{\text{L}}} = -\frac{Q_{\text{H}}}{T_{\text{H}}} + \frac{Q_{\text{H}}}{T_{\text{H}}} = \boxed{0}$$

A numeric calculation might give a very small number due to not keeping all digits in the calculation.

44. When throwing two dice, there are 36 possible microstates.

(*a*) The possible microstates that give a total of 4 are (1)(3), (2)(2), and (3)(1). Thus the probability of getting a 5 is $3/36 = \boxed{1/12}$.

(*b*) The possible microstates that give a total of 10 are (4)(6), (5)(5), and (6)(4). Thus the probability of getting a 10 is $3/36 = \boxed{1/12}$.

45. From the table below, we see that there are a total of $2^6 = 64$ microstates.

Macrostate	Possible Micostates (H = heads, T = tails)						Number of Microstates
6 heads, 0 tails	H H H H H H						1
5 heads, 1 tails	H H H H H T	H H H H T H	H H H T H H	H H T H H H	H T H H H H	T H H H H H	6
4 heads, 2 tails	H H H H T T	H H H T H T	H H T H H T	H T H H H T	T H H H H T		15
	H H H T T H	H H T H T H	H T H H T H	T H H H T H	HHTTH H		
	H T H T H H	T H H T H H	H T T H H H	T H T H H H	T T H H H H		
3 heads, 3 tails	H H H T T T	H H T H T T	H T H H T T	T H H H T T	H H T T H T		20
	H T H T H T	T H H T H T	H T T H H T	T H T H H T	T T H H H T		
	T T T H T H	T T H T H H	T H T T H H	H T T T H H	T T H H T H		
	T H T H T H	H T T H T H	T H H T T H	H T H T T H	H H T T TH		
2 heads, 4 tails	T T T T H H	T T T H T H	T T H T T H	T H T T T H	H T T T T H		15
	T T T H H T	T T H T H T	T H T T H T	H T T T H T	T T H H T T		
	T H T H T T	H T T H T T	T H H T T T	H T H T T T	H H T T T T		
1 heads, 5 tails	T T T T T H	T T T T H T	T T T H T T	T T H T T T	T H T T T T	H T T T T T	6
0 heads, 6 tails	T T T T T T						1

(*a*) The probability of obtaining three heads and three tails is $\boxed{20/64}$ or $\boxed{5/16}$.

(*b*) The probability of obtaining six heads is $\boxed{1/64}$.

46. (*a*) From the table below, we see that there are 10 macrostates and a total of 27 microstates.

Macrostate	Macrostate (r = red, o = orange, g = green)			Number of Microstates
3 red, 0 orange, 10 0 green	r r r			1
2 red, 1 orange, 10 0 green	r r o	r o r	o r r	3
2 red, 0 orange, 10 1 green	r r g	r g r	g r r	3
1 red, 2 orange, 10 0 green	r o o	o r o	o o r	3
1 red, 0 orange, 10 2 green	r g g	g r g	g g r	3
1 red, 1 orange, 10 1 green	r o g o g r	r g o g r o	o r g g o r	6
0 red, 3 orange, 10 0 green	o o o			1
0 red, 2 orange, 10 1 green	g o o	o g o	o o g	3
0 red, 1 orange, 10 2 green	o g g	g o g	g g o	3
0 red, 0 orange, 10 3 green	g g g			1

(*b*) The probability of obtaining all 3 beans red is $\boxed{1/27}$.

(*c*) The probability of obtaining 2 greens and 1 orange is $\boxed{3/27}$ or $\boxed{1/19}$.

47. The required area is $\left(24\dfrac{10^3\ \text{W}\cdot\text{h}}{\text{day}}\right)\left(\dfrac{1\ \text{day}}{9\ \text{h Sun}}\right)\left(\dfrac{1\ \text{m}^2}{40\ \text{W}}\right) = 66.7\ \text{m}^2 \approx \boxed{70\ \text{m}^2}.$ A small house with 1000 ft^2 of floor space and a roof tilted at 30° would have a roof area of

$(1000\ \text{ft}^2)\left(\dfrac{1}{\cos 30°}\right)\left(\dfrac{1\ \text{m}}{3.28\ \text{ft}}\right)^2 = 110\ \text{m}^2,$ which is about 50% larger than the area needed, so $\boxed{\text{the cells}}$

$\boxed{\text{would fit on the house}}$. But not all parts of the roof would have 9 hours of sunlight, so more than the minimum number of cells would be needed.

48. (*a*) Assume that there are no dissipative forces present, so the energy required to pump the water to the lake is just the gravitational potential energy of the water.

$$\text{PE}_{\text{grav}} = mgh = (1.00\times10^5\ \text{kg/s})(10.0\ \text{h})(9.80\ \text{m/s}^2)(115\ \text{m}) = 1.127\times10^9\ \text{W}\cdot\text{h}$$
$$\approx \boxed{1.13\times10^6\ \text{kW}\cdot\text{h}}$$

(*b*) $$\frac{(1.127\times10^6\ \text{kW}\cdot\text{h})(0.75)}{14\ \text{h}} = \boxed{6.0\times10^4\ \text{kW}} = 60\ \text{MW}$$

49. We assume that the electrical energy comes from the 100% effective conversion of the gravitational potential energy of the water.

$$W = mgh \quad \rightarrow$$
$$P = \frac{W}{t} = \frac{m}{t}gh = \rho\frac{V}{t}gh = (1.00\times10^3\ \text{kg/m}^3)(32\ \text{m}^3/\text{s})(9.80\ \text{m/s}^2)(48\ \text{m})$$
$$= \boxed{1.5\times10^7\ \text{W}} = 15\ \text{MW}$$

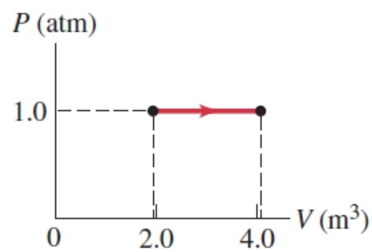
50. (*a*) The work done at constant pressure is Eq. 15–3, $W = P\Delta V$.

$$W = P\Delta V$$
$$= (1.00\ \text{atm})(1.01\times10^5\ \text{Pa/atm})(4.1\ \text{m}^3 - 1.9\ \text{m}^3)$$
$$= 2.22\times10^5\ \text{J} \approx \boxed{2.2\times10^5\ \text{J}}$$

(*b*) Use the first law of thermodynamics, Eq. 15–1.

$$\Delta U = Q - W = 5.80\times10^5\ \text{J} - 2.22\times10^5\ \text{J} = \boxed{3.6\times10^5\ \text{J}}$$

(*c*) See the adjacent graph.



$\boxed{51.}$ The coefficient of performance for an ideal refrigerator is given by Eq. 15–6c, with temperatures in kelvins. Use that expression to find the temperature inside the refrigerator.

$$\text{COP} = \frac{T_{\text{L}}}{T_{\text{H}} - T_{\text{L}}} \quad \rightarrow \quad T_{\text{L}} = T_{\text{H}}\frac{\text{COP}}{1+\text{COP}} = [(32+273)\ \text{K}]\frac{4.6}{5.6} = 251\ \text{K} = \boxed{-22^\circ\text{C}}$$

52. The minimum value for T_{H} would occur if the engine were a Carnot engine. We calculate the efficiency of the engine from the given data and use this as a Carnot efficiency to calculate T_{H}.

$$\frac{W}{t} = \underset{\substack{\text{(to move}\\\text{car)}}}{P_{\text{output}}} = 7000\ \text{W};\quad \frac{Q_{\text{H}}}{t} = \underset{\substack{\text{(from}\\\text{gasoline)}}}{P_{\text{input}}} = \left(3.2\times10^7\ \frac{\text{J}}{\text{L}}\right)\left(\frac{1\ \text{L}}{17{,}000\ \text{m}}\right)\left(\frac{21.8\ \text{m}}{1\ \text{s}}\right) = 41{,}035\ \text{W}$$

$$e = \frac{W}{Q_{\text{H}}} = \frac{\underset{\substack{\text{(to move}\\\text{car)}}}{P_{\text{output}}}}{\underset{\substack{\text{(from}\\\text{gasoline)}}}{P_{\text{input}}}} = \frac{7000\ \text{W}}{41{,}035\ \text{W}} = 1 - \frac{T_{\text{L}}}{T_{\text{H}}} \quad \rightarrow \quad T_{\text{H}} = \frac{T_{\text{L}}}{(1-e)} = \frac{(273+25)\ \text{K}}{\left(1 - \frac{7000\ \text{W}}{41{,}035\ \text{W}}\right)} = 359\ \text{K} = \boxed{86^\circ\text{C}}$$

53\. (*a*) The heat that must be removed from the water (Q_L) is found in three parts—that from cooling the liquid water to the freezing point, freezing the liquid water, and then cooling the ice to the final temperatures.

$$Q_L = m(c_{liquid}\Delta T_{liquid} + L_F + c_{ice}\Delta T_{ice})$$
$$= (0.65\text{ kg})\left[\begin{matrix}(4186\text{ J/kg}\cdot\text{C°})(25\text{ C°}) + (3.33\times10^5\text{ J/kg}) \\ +(2100\text{ J/kg}\cdot\text{C°})(17\text{ C°})\end{matrix}\right] = 3.077\times10^5\text{ J}$$

The Carnot efficiency can be used to find the work done by the refrigerator.

$$e = 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} = \frac{W}{W+Q_L} \rightarrow$$

$$W = Q_L\left(\frac{T_H}{T_L} - 1\right) = (3.077\times10^5\text{ J})\left(\frac{(25+273)\text{ K}}{(-17+273)\text{ K}} - 1\right) = 5.048\times10^4\text{ J} \approx \boxed{5.0\times10^4\text{ J}}$$

(*b*) Use the compressor wattage to calculate the time. The compressor power can be expressed as one-fourth of the nominal power, since it only runs 25% of the time.

$$P = W/t \rightarrow t = W/P = 5.048\times10^4\text{ J/[(105 W) 0.25]} = 1923\text{ s} \approx \boxed{32\text{ min}}$$

54\. (*a*) Calculate the Carnot efficiency for an engine operated between the given temperatures.

$$e_{ideal} = 1 - \frac{T_L}{T_H} = 1 - \frac{(273+4)\text{ K}}{(273+27)\text{ K}} = 0.077 = \boxed{7.7\%}$$

(*b*) Such an engine might be feasible in spite of the low efficiency because of the large volume of "fuel" (ocean water) available. Ocean water would appear to be an almost inexhaustible source of heat energy.

(*c*) The pumping of water between radically different depths would probably move smaller sea-dwelling creatures from their natural location, perhaps killing them in the transport process. This might affect the food chain of other local sea-dwelling creatures. Mixing the water at different temperatures will also disturb the environment of sea-dwelling creatures. There is a significant dynamic of energy exchange between the ocean and the atmosphere, so any changing of surface temperature water might affect at least the local climate, and perhaps also cause larger-scale climate changes.

55\. We start with Eq. 15–6a for the COP of a refrigerator. The heat involved is the latent heat of fusion for water.

$$\text{COP} = \frac{Q_L}{W} \rightarrow W = \frac{Q_L}{\text{COP}} \rightarrow$$

$$W/t = \frac{Q_L/t}{\text{COP}} = \frac{5\text{ tons}}{0.18\text{ COP}_{ideal}} = \frac{5(909\text{ kg/d})(3.33\times10^5\text{ J/kg})}{0.18\left(\frac{273\text{ K}+22\text{ K}}{13\text{ K}}\right)} = 3.705\times10^8\text{J/d}$$

$$\text{cost/h} = (3.705\times10^8\text{ J/d})\left(\frac{1\text{ d}}{24\text{ h}}\right)\left(\frac{1\text{ kWh}}{3.600\times10^6\text{ J}}\right)\left(\frac{\$0.10}{\text{kWh}}\right) = \boxed{\$0.43/\text{h}}$$

56\. Take the energy transfer to use as the initial kinetic energy of the cars, because this energy becomes "unusable" after the collision—it is transferred to the environment.

$$\Delta S = \frac{Q}{T} = \frac{2(\frac{1}{2}mv_0^2)}{T} = \frac{(1100\text{ kg})\left[(85\text{ km/h})\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right)\right]^2}{(20+273)\text{ K}} = 2093\text{ J/K} \approx \boxed{2100\text{ J/K}}$$

57. (*a*) The equilibrium temperature is found using calorimetry, from Chapter 14. The heat lost by the water is equal to the heat gained by the aluminum.

$$m_{H_2O}c_{H_2O}(T_{iH_2O} - T_f) = m_{Al}c_{Al}(T_f - T_{iAl}) \quad \rightarrow$$

$$T_f = \frac{m_{Al}c_{Al}T_{iAl} + m_{H_2O}c_{H_2O}T_{iH_2O}}{m_{Al}c_{Al} + m_{H_2O}c_{H_2O}}$$

$$= \frac{(0.11\text{ kg})(900\text{ J/kg}\cdot\text{C}^\circ)(35^\circ\text{C}) + (0.15\text{ kg})(4186\text{ J/kg}\cdot\text{C}^\circ)(45^\circ\text{C})}{(0.11\text{ kg})(900\text{ J/kg}\cdot\text{C}^\circ) + (0.15\text{ kg})(4186\text{ J/kg}\cdot\text{C}^\circ)} = 43.64^\circ\text{C} \approx \boxed{44^\circ\text{C}}$$

(*b*) The amount of heat lost by the aluminum, and gained by the water, is

$$Q = m_{H_2O}c_{H_2O}(T_{i\,H_2O} - T_f) = (0.15\text{ kg})(4186\text{ J/kg}\cdot\text{C}^\circ)(45^\circ\text{C} - 43.64^\circ\text{C}) = 853.9\text{ J}$$

In calculating the entropy change, we need to use estimates for the temperatures of the water and the aluminum since their temperatures are not constant. We will use their average temperatures.

$$T_{\substack{H_2O\\ \text{avg}}} = (45^\circ\text{C} + 43.64^\circ\text{C})/2 = 44.32^\circ\text{C}; \quad T_{\substack{Al\\ \text{avg}}} = (35^\circ\text{C} + 43.64^\circ\text{C})/2 = 39.32^\circ\text{C}$$

$$\Delta S = \Delta S_{Al} + \Delta S_{H_2O} = -\frac{Q}{T_{\substack{H_2O\\ \text{avg}}}} + \frac{Q}{T_{\substack{Al\\ \text{avg}}}} = (853.9\text{ J})\left(\frac{1}{(39.32+273)\text{ K}} \quad \frac{1}{(44.32+273)\text{ K}}\right)$$

$$= 0.0431\text{ J/K} \approx \boxed{0.043\text{ J/K}}$$

58. The efficiency is given by Eq. 15–4a, $e = W/Q_H = \frac{W/t}{Q_H/t}$, so the input power (Q_H/t) and the useful power (W/t) are needed.

$$W/t = (25\text{ hp})(746\text{ W/hp}) = 1.865\times10^4\text{ J/s}$$

$$Q_H/t = \left(\frac{3.0\times10^4\text{ kcal}}{1\text{ gal}}\right)\left(\frac{1\text{ gal}}{41\text{ km}}\right)\left(\frac{110\text{ km}}{1\text{ h}}\right)\left(\frac{4186\text{ J}}{1\text{ kcal}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 9.359\times10^4\text{ J/s}$$

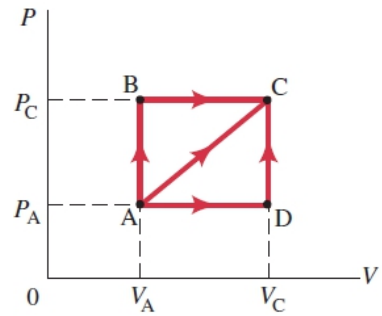
$$e = \frac{W/t}{Q_H/t} = \frac{1.865\times10^4\text{ J/s}}{9.359\times10^4\text{ J/s}} = 0.199 \approx \boxed{20\%}$$

59. Find the original intake temperature T_{H1} from the original Carnot efficiency and then recalculate the intake temperature for the new Carnot efficiency, T_{H2}, using the same exhaust temperature. Use Eq. 15–5 for the Carnot efficiency.

$$e_1 = 1 - \frac{T_L}{T_{H1}} \rightarrow T_{H1} = \frac{T_L}{1-e_1} \qquad e_2 = 1 - \frac{T_L}{T_{H2}} \rightarrow T_{H2} = \frac{T_L}{1-e_2}$$

$$T_{H2} - T_{H1} = T_L\left(\frac{1}{1-e_2} - \frac{1}{1-e_1}\right) = (273\text{ K} + 20\text{ K})\left(\frac{1}{1-0.35} - \frac{1}{1-0.25}\right) = 60.10\text{ K} \approx \boxed{60\text{ K}}$$

60. Note that there is NO work done as the gas goes from state A to state B or state D to state C, because there is no volume change. In general, the work done can be found from the area under the *PV* curve representing the process under consideration.



(*a*) $W_{ADC} = \boxed{P_A(V_C - V_A)}$

(*b*) $W_{ABC} = \boxed{P_C(V_C - V_A)}$

(*c*) $W_{AC} = \boxed{\tfrac{1}{2}(P_C + P_A)(V_C - V_A)}$

(Use the formula for the area of a trapezoid.)

61. (*a*) The exhaust heating rate is found from the delivered power and the efficiency. Use the output energy with Eq. 14–2, $Q = mc\Delta T = \rho Vc\Delta T$, to calculate the volume of air that is heated. The efficiency is given by Eq. 15–4a.

$$e = W/Q_H = W/(Q_L + W) \quad \rightarrow \quad Q_L = W(1/e - 1) \quad \rightarrow$$

$$Q_L/t = (W/t)(1/e - 1) = (8.5\times10^8 \text{ W})(1/0.38 - 1) = 1.387\times10^9 \text{ W}$$

$$Q_L = mc\Delta T \quad \rightarrow \quad Q_L/t = \frac{mc\Delta T}{t} = \frac{\rho Vc\Delta T}{t} \quad \rightarrow \quad V/t = \frac{(Q_L/t)}{\rho c\,\Delta T}$$

The change in air temperature is $7.0\ \text{C}°$. The heated air is at a constant pressure of 1 atm.

$$V/t = \frac{(Q_L/t)t}{\rho c\Delta T} = \frac{(1.387\times10^9 \text{ W})(8.64\times10^4 \text{ s/day})}{(1.3 \text{ kg/m}^3)(1.0\times10^3 \text{ J/kg}\cdot\text{C}°)(7.0 \text{ C}°)}$$

$$= 1.317\times10^{10} \text{ m}^3/\text{day}\left(\frac{10^{-9} \text{ km}^3}{1 \text{ m}^3}\right) = 13.17 \text{ km}^3/\text{day} \approx \boxed{13 \text{ km}^3/\text{day}}$$

This could affect the local climate around the power plant.

(*b*) If the air is 180 m thick, find the area by dividing the volume by the thickness.

$$A = \frac{\text{Volume}}{\text{thickness}} = \frac{13.17 \text{ km}^3}{0.18 \text{ km}} = \boxed{73 \text{ km}^2}$$

This would be a square of approximately 8.5 km or 5.3 miles to a side. Thus the local climate for a few miles around the power plant might be heated significantly.

62. (*a*) The exhaust heating rate can be found from the delivered power *P* and the Carnot efficiency. Then use Eq. 14–2, $Q = mc\Delta T$, to calculate the temperature change of the cooling water. Eqs. 15–4 and 15–5 for efficiency are also used.

$$e = 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} = \frac{W}{Q_L + W} \quad \rightarrow \quad Q_L = W\frac{T_L}{T_H - T_L} \quad \rightarrow \quad Q_L/t = W/t\,\frac{T_L}{T_H - T_L} = P\frac{T_L}{T_H - T_L}$$

$$Q_L = mc\Delta T \quad \rightarrow \quad Q_L/t = \frac{m}{t}c\Delta T = \rho\frac{V}{t}c\Delta T$$

Equate the two expressions for Q_L/t, and solve for ΔT.

$$P\frac{T_L}{T_H - T_L} = \rho\frac{V}{t}c\Delta T \quad \rightarrow \quad \Delta T = \frac{P}{\rho\frac{V}{t}c}\left(\frac{T_L}{T_H - T_L}\right)$$

$$= \frac{8.8\times10^8 \text{ W}}{(1.0\times10^3 \text{ kg/m}^3)(37 \text{ m}^3/\text{s})(4186 \text{ J/kg}\cdot\text{C}°)}\frac{285 \text{ K}}{(625 \text{ K} - 285 \text{ K})} = 4.763 \text{ K} = \boxed{4.8 \text{ C}°}$$

(*b*) The addition of heat per kilogram for the downstream water is $Q_L/t = c\Delta T$. We use the "average" temperature of the river water for the calculation: $T = T_0 + \frac{1}{2}\Delta T$. Now the entropy increase can be calculated using Eq. 15–8.

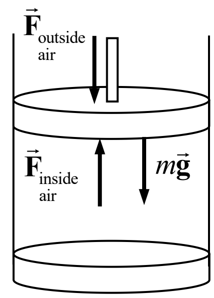
$$\Delta S = \frac{Q}{T} = \frac{c\Delta T}{T_0 + \frac{1}{2}\Delta T} = \frac{(4186\ \text{J/kg}\cdot\text{C}°)(4.763\ \text{K})}{[285 + \frac{1}{2}(4.763)]\ \text{K}} = 69.38\ \text{J/kg}\cdot\text{K} \approx \boxed{69\ \text{J/kg}\cdot\text{K}}$$

63. The net force on the piston must be 0, so the weight of the piston must be equal to the net force exerted by the gas pressures on both sides of the piston. See the free-body diagram.

$$\sum F = F_{\substack{\text{inside}\\ \text{air}}} - F_{\substack{\text{outside}\\ \text{air}}} - mg = 0 = P_{\text{inside}}A - P_{\text{outside}}A - mg = 0$$

$$P_{\text{inside}} = P_{\text{outside}} + \frac{mg}{A} = (1.0\ \text{atm})\left(1.01\times10^5\ \frac{\text{Pa}}{\text{atm}}\right) + \frac{(0.15\ \text{kg})(9.8\ \text{m/s}^2)}{0.080\ \text{m}^2}$$

$$= 1.0102\times10^5\ \text{Pa} \approx 1\ \text{atm}$$



We see that the weight of the piston is negligible compared to the pressure forces.

When the gas is heated, we assume that the inside pressure does not change. Since the weight of the piston does not change, and the outside air pressure does not change, the inside air pressure cannot change. Thus the expansion is at a constant pressure, so the work done can be calculated. Use this with the first law of thermodynamics to find the heat required for the process.

$$U = \tfrac{3}{2}nRT = \tfrac{3}{2}PV \quad \rightarrow \quad \Delta U = \tfrac{3}{2}P\Delta V = Q - W$$

$$Q = \Delta U + W = \tfrac{3}{2}P\Delta V + P\Delta V = \tfrac{5}{2}P\Delta V = \tfrac{5}{2}PA\Delta y = 2.5(1.01\times10^5\ \text{Pa})(0.080\ \text{m}^2)(1.0\times10^{-2}\ \text{m})$$

$$= 202\ \text{J} \approx \boxed{2.0\times10^2\ \text{J}}$$

64. (*a*) Multiply the power, the time, and the mass per joule relationship for the fat.

$$(95\ \text{J/s})(3600\ \text{s/h})(24\ \text{h/d})(1.0\ \text{kg fat}/3.7\times10^7\ \text{J}) = 0.2218\ \text{kg/d} \approx \boxed{0.22\ \text{kg/d}}$$

(*b*) $1.0\ \text{kg}(1\ \text{d}/0.2218\ \text{kg}) = \boxed{4.5\ \text{days}}$

65. (*a*) For each engine, the efficiency is given by $e = 0.65e_{\text{Carnot}}$. Thus

$$e_1 = 0.65e_{\text{C-1}} = 0.65\left(1 - \frac{T_{\text{L1}}}{T_{\text{H1}}}\right) = 0.65\left[1 - \frac{(440+273)\ \text{K}}{(750+273)\ \text{K}}\right] = 0.197$$

$$e_2 = 0.65e_{\text{C-2}} = 0.65\left(1 - \frac{T_{\text{L2}}}{T_{\text{H2}}}\right) = 0.65\left[1 - \frac{(270+273)\ \text{K}}{(415+273)\ \text{K}}\right] = 0.137$$

For the first engine, the input heat is from the coal.

$$W_1 = e_1Q_{\text{H1}} = e_1Q_{\text{coal}} \quad \text{and} \quad Q_{\text{L1}} = Q_{\text{H1}} - W_1 = (1-e_1)Q_{\text{coal}}$$

For the second engine, the input heat is the output heat from the first engine.

$$W_2 = e_2Q_{\text{H2}} = e_2Q_{\text{L1}} = e_2(1-e_1)Q_{\text{coal}}$$

Add the two work expressions together and solve for Q_{coal}.

$$W_1 + W_2 = e_1 Q_{\text{coal}} + e_2(1-e_1)Q_{\text{coal}} = (e_1 + e_2 - e_1 e_2)Q_{\text{coal}}$$

$$Q_{\text{coal}} = \frac{W_1 + W_2}{e_1 + e_2 - e_1 e_2} \rightarrow Q_{\text{coal}}/t = \frac{(W_1 + W_2)/t}{e_1 + e_2 - e_1 e_2}$$

Calculate the rate of coal use from the required rate of input energy, Q_{coal}/t.

$$Q_{\text{coal}}/t = \frac{950\times10^6\ \text{W}}{0.197 + 0.137 - (0.197)(0.137)} = 3.094\times10^9\ \text{J/s}$$

$$(3.094\times10^9\ \text{J/s})\left(\frac{1\ \text{kg}}{2.8\times10^7\ \text{J}}\right) = 110.5\ \text{kg/s} \approx \boxed{110\ \text{kg/s}}$$

(*b*) The heat exhausted into the water will make the water temperature rise according to Eq. 14–2. The heat exhausted into water is the heat from the coal minus the useful work.

$$Q_{\text{exhaust}} = Q_{\text{coal}} - W;\quad Q_{\text{exhaust}} = m_{H_2O}c_{H_2O}\Delta T_{H_2O} \rightarrow m_{H_2O} = \frac{Q_{\text{exhaust}}}{c_{H_2O}\Delta T_{H_2O}} = \frac{Q_{\text{coal}} - W}{c_{H_2O}\Delta T_{H_2O}}$$

$$\frac{m_{H_2O}}{t} = \frac{(Q_{\text{coal}}/t) - (W/t)}{c_{H_2O}\Delta T_{H_2O}} = \frac{(3.094\times10^9\ \text{J/s}) - (9.50\times10^8)\ \text{J/s}}{(4186\ \text{J/kg}\cdot\text{C°})(4.5\ \text{C°})} = 1.13\times10^5\ \text{kg/s}$$

$$= \left(1.138\times10^5\ \frac{\text{kg}}{\text{s}}\right)\left(3600\ \frac{\text{s}}{\text{h}}\right)\left(\frac{1\ \text{m}^3}{1000\ \text{kg}}\right)\left(\frac{1\ \text{L}}{10^{-3}\ \text{m}^3}\right)\left(\frac{1\ \text{gal}}{3.785\ \text{L}}\right) = \boxed{1.1\times10^8\ \text{gal/h}}$$

66. According to Table 15–2, riding a bicycle at a racing pace requires an input of 1270 watts. That value is used to calculate the work input to the heat pump. The coefficient of performance equation, Eq. 15–7, is then used to calculate the heat delivered by the heat pump.

$$\text{COP} = \frac{Q_H}{W} \rightarrow Q_H = W(\text{COP}) = \left(1270\ \frac{\text{J}}{\text{s}}\right)(1800\ \text{s})(2.0) = 4.572\times10^6\ \text{J} \approx \boxed{4.6\times10^6\ \text{J}}$$

67. The radiant energy that enters the room is the heat to be removed at the low temperature. It can be related to the work necessary to remove it through the ideal efficiency, Eq. 15–5. We then subtract the two rates of doing work to find the savings.

$$e = 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} = \frac{W}{W + Q_L} \rightarrow W = Q_L\left(\frac{T_H}{T_L} - 1\right) \rightarrow W/t = Q_L/t\left(\frac{T_H}{T_L} - 1\right)$$

$$(W/t)_{4800} = (4800\ \text{W})\left(\frac{T_H}{T_L} - 1\right)\quad (W/t)_{500} = (500\ \text{W})\left(\frac{T_H}{T_L} - 1\right)$$

$$(W/t)_{\text{savings}} = (W/t)_{4800} - (W/t)_{500} = (4800\ \text{W} - 500\ \text{W})\left(\frac{(273+32)\ \text{K}}{(273+21)\ \text{K}} - 1\right) = 160.9\ \text{W} \approx \boxed{160\ \text{W}}$$

68. (*a*) The total rate of adding heat to the house by the heat pump must equal the rate of heat loss by conduction.

$$\frac{Q_L + W}{\Delta t} = (650\ \text{W/C°})(T_{\text{in}} - T_{\text{out}})$$

Since the heat pump is ideal, we have the following from the efficiency.

$$1-\frac{T_{\text{outside}}}{T_{\text{inside}}}=1-\frac{Q_{\text{L}}}{Q_{\text{H}}}=1-\frac{Q_{\text{L}}}{Q_{\text{L}}+W}=\frac{W}{Q_{\text{L}}+W} \rightarrow Q_{\text{L}}+W=W\frac{T_{\text{inside}}}{T_{\text{inside}}-T_{\text{outside}}}$$

Combine these two expressions and solve for T_{out}.

$$\frac{Q_{\text{L}}+W}{\Delta t}=(650\text{ W/C°})(T_{\text{inside}}-T_{\text{outside}})=\frac{W}{\Delta t}\frac{T_{\text{inside}}}{(T_{\text{inside}}-T_{\text{outside}})} \rightarrow$$

$$(T_{\text{inside}}-T_{\text{outside}})^2=\frac{W}{\Delta t}\frac{T_{\text{inside}}}{(650\text{ W/C°})} \rightarrow$$

$$T_{\text{outside}}=T_{\text{inside}}-\sqrt{\frac{W}{\Delta t}\frac{T_{\text{inside}}}{(650\text{ W/C°})}}=295\text{ K}-\sqrt{(1500\text{ W})\frac{295\text{ K}}{(650\text{ W/C°})}}=269\text{ K}=\boxed{-4°\text{C}}$$

(*b*) If the outside temperature is $8°\text{C}$, then the rate of heat loss by conduction is found to be $(650\text{ W/C°})(14\text{ C°})=9100\text{ W}$. The heat pump must provide this much power to the house in order for the house to stay at a constant temperature. That total power is $(Q_{\text{L}}+W)/\Delta t$. Use this to solve for the rate at which the pump must do work.

$$(Q_{\text{L}}+W)/\Delta t=\frac{W}{\Delta t}\left(\frac{T_{\text{inside}}}{T_{\text{inside}}-T_{\text{outside}}}\right)=9100\text{ W} \rightarrow$$

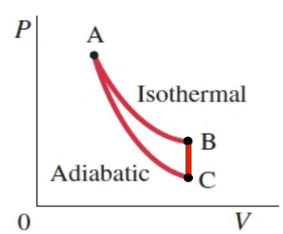
$$\frac{W}{\Delta t}=9100\text{ W}\left(\frac{T_{\text{inside}}-T_{\text{outside}}}{T_{\text{inside}}}\right)=9100\text{ W}\left(\frac{14\text{ K}}{295\text{ K}}\right)=432\text{ W}$$

Since the maximum power the pump can provide is 1500 W, the pump must work $\frac{432\text{ W}}{1500\text{ W}}=0.29$ or 29% of the time.

Solutions to Search and Learn Problems

1. If water vapor condenses on the outside of a cold glass of water, the internal energy of the water vapor has decreased, by an amount equal to the heat of vaporization of the water vapor times the mass of water that has condensed. Heat energy left the water vapor, causing it to condense, and heat energy entered the glass of water and the air, causing them to get slightly warmer. No work is done, but heat is exchanged.

2. The first step is an isothermal expansion—the volume increases and the pressure decreases as the temperature stays constant. It is represented by the line from A to B on the diagram. The second step must be at a constant volume since no work is done, so is a vertical line. It is represented by the line from B to C on the diagram. The third step is adiabatic and must be a compression since the work done is negative. It is represented by the line from C to A on the diagram.



3. To find the mass of water removed, find the energy that is removed from the low-temperature reservoir from the work input and the Carnot efficiency. Then use the latent heat of vaporization to determine the mass of water from the energy required for the condensation. Note that the heat of vaporization used is that given in Chapter 14 for evaporation at 20°C.

$$e = 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} = \frac{W}{W + Q_L} \quad \rightarrow \quad Q_L = W\frac{T_L}{(T_H - T_L)} = mL_V$$

$$m = \frac{W}{L_V}\frac{T_L}{(T_H - T_L)} = \frac{(600\ \text{W})(3600\ \text{s})}{(2.45\times10^6\ \text{J/kg})}\frac{(273+8)\ \text{K}}{17\ \text{K}} = 14.6\ \text{kg} \approx \boxed{15\ \text{kg}}$$

4. The energy necessary to heat the water can be obtained using Eq. 14–2. The specific heat of the water is $4186\ \text{J/kg}\cdot\text{C}°$.

$$Q = mc\Delta T = (1.0\ \text{kg})(4186\ \text{J/kg}\cdot\text{C}°)(95°\text{C} - 25°\text{C}) = 2.9302\times10^5\ \text{J}$$

The intensity of sunlight at the Earth's surface is $\sim 1000\ \text{W/m}^2$. The photovoltaic panel can therefore produce energy at this rate.

$$\frac{Q}{t} = (1000\ \text{W/m}^2)(1.5\ \text{m}^2)(0.20) = 300\ \text{J/s}$$

Dividing the energy needed to heat the water by the rate at which energy is available will give the time required to heat the water using the photovoltaic cell.

$$t = \frac{Q}{Q/t} = \frac{2.9302\times10^5\ \text{J}}{300\ \text{J/s}} = \boxed{977\ \text{s} \approx 16\ \text{minutes}}$$

Using the curved mirror allows all of the energy in the sunlight $[(1000\ \text{W/m}^2)(1.5\ \text{m}^2) = 1500\ \text{J/s}]$ to go into heating the water.

$$t = \frac{Q}{Q/t} = \frac{2.9302\times10^5\ \text{J}}{1500\ \text{J/s}} = \boxed{195\ \text{s} \approx 3\ \text{minutes}}$$