

CHAPTER 15: The Laws of Thermodynamics

Answers to Questions

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. Heat energy has left the water vapor, causing it to condense, and heat energy has entered the glass of water, and the air, causing them to get slightly warmer. No work is done, but heat is exchanged.
2. During compression, work is done on the gas. Assuming that there is no heat flow to or from the gas (since the process is quick), by conservation of energy (the first law of thermodynamics) the work done on the gas becomes internal energy of the gas, and so the temperature of the gas is increased. During expansion, work is done by the gas on its surroundings. Again assuming that there is no heat flow to or from the gas, by conservation of energy, the work is done by the gas at the expense of the internal energy of the gas, and so the temperature of the gas is decreased.
3. Since the process is isothermal, there is no change in the internal energy of the gas. Thus $\Delta U = Q - W = 0 \rightarrow Q = W$, and 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.
4. 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 would be an example of this situation.
5. If the gas is compressed adiabatically, 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 $\Delta U = -W$. 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.
6. Mechanical energy can be transformed completely into heat. As 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.
7. 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, the oven is just heating a bigger volume than usual. 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. 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.

8. This definition of efficiency is not useful, because with this definition, if the exhaust heat Q_L is less than the work done W (which is possible), the “efficiency” would exceed unity. Efficiency should be comparing to the heat input, not the heat output.
9. (a) In an internal combustion engine, the high temperature reservoir is the ignited gas-air mixture. The low temperature reservoir is the gases exhausted from the cylinder into the atmosphere.
 (b) In a steam engine, the high temperature reservoir is the heated, high-pressure steam from the boiler. The low temperature reservoir is the low-pressure steam from the exhaust.
10. The efficiency of a Carnot engine is given by Eq. 15-5, $e = 1 - \frac{T_L}{T_H}$. Both a decrease in T_L and an increase in T_H would cause the value of T_L/T_H to decrease, increasing the efficiency. Since $T_L < T_H$, the 10°C change is a larger percentage of change for T_L , and so will change the fraction more than the same numeric increase in the denominator. Note $e_1 = 1 - \frac{T_L - 10}{T_H} = \frac{T_H - T_L + 10}{T_H}$ and $e_2 = 1 - \frac{T_L}{T_H + 10} = \frac{T_H - T_L + 10}{T_H + 10}$. Both efficiencies have the same numerator, but e_2 has a larger denominator, and so $e_1 > e_2$.
11. To utilize the thermal energy in the ocean waters, 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, 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 or Antarctic water were to be used, the same type of major difficulties would be involved because of the large distances involved.
12. (a) If a gas expands adiabatically, there is no heat transfer, and therefore $\Delta S = 0$ by Eq. 15-8, $\Delta S = Q/T$.
 (b) If a gas expands isothermally, 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, and so $\Delta S > 0$ – the entropy of the gas increases.
13. The adiabatic expansion results in no change in entropy, since there is no heat transfer. The isothermal expansion requires heat flow into the gas to compensate for the work that the gas does, and so the entropy of the gas ($\Delta S = Q/T$) increases more for the isothermal expansion.
14. (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) The conversion of mechanical energy to heat energy by friction; i.e., a sliding object decreasing in speed and eventually stopping, and the surfaces of contact getting warmer.
 (d) A pile of compost decomposing.
 The reverse of these processes is not observed.

15. 1 kg of liquid iron has more entropy, because the atoms in liquid iron are less “ordered” than those in solid iron. Also, heat had to be added to solid iron in order to melt it, and $\Delta S = Q/T$.
16. (a) If the lid is removed from a bottle of chlorine gas, the gas molecules will diffuse out of the mouth of the bottle, and eventually spread out uniformly in whatever volume to which they are confined.
- (b) The reverse process, that of individual chlorine gas molecules in a closed volume spontaneously entering a small volume, never happens. The probability of the gas molecules all entering the bottle is infinitesimal compared to the probability of the gas molecules being uniformly spread throughout the room. The reverse process would require a spontaneous decrease in entropy.
- (c) Some other examples of irreversibility: the shuffling of an ordered deck of cards; the diffusion of dye in a liquid; the toppling of buildings during an earthquake.
17. 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 2nd 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 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 into the device will cause the device to heat up warmer than the room, and then heat will be transferred to the room. One very simple device that could do what is described in the problem 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 can be blown out of the box by a fan. But after the ice melts, the only end result is that the fan motor would heat the air.
18. (a) 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.
- (b) Water on the sidewalk coalesces into droplets, are propelled upward, and rise into the air.
- (c) Popcorn is placed in the refrigerator, and it “unpops”, changing backed into uncooked kernels.
- (d) A house got warmer in the winter while the outdoors got colder, due to heat moving from the outdoors to inside the house.
19. While the state of the papers has gone 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.
20. 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 1st 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 2nd law is that there is no heat engine that is 100% efficient. Even though the 1st law is satisfied by an engine that takes in 100 J of heat and outputs 100 J of work, the 2nd law says that is impossible. If 100 J of heat were taken in, less than 100 J of work can be output from the heat engine, even if it is an ideal heat engine. Some energy will be “lost” as exhaust energy.

21. In an action movie, seeing a building or car go from an exploded state to an un-exploded state. In a movie with vehicle crashes, seeing two collided vehicles separate from each other, becoming un-wrecked as they separate. Watching someone “un-write” something on a piece of paper – moving a pen over paper, taking away written marks as the pen moves.
22. 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 will have an increase in entropy that is larger than the decrease in entropy of the molecules, and so overall, the second law is still satisfied, and the entropy of the entire system will increase.

Solutions to Problems

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) Since the temperature does not change, $\Delta U = 0$

(b) $\Delta U = Q - W \rightarrow Q = \Delta U + W = 0 + 3.40 \times 10^3 \text{ J} = 3.40 \times 10^3 \text{ J}$

2. (a) The work done by a gas at constant pressure is found from Eq. 15-3.

$$W = P\Delta V = (1 \text{ atm}) \left(\frac{1.01 \times 10^5 \text{ Pa}}{1 \text{ atm}} \right) (18.2 \text{ m}^3 - 12.0 \text{ m}^3) = 6.262 \times 10^5 \text{ J} \approx 6.3 \times 10^5 \text{ J}$$

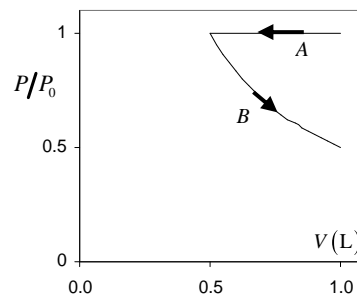
- (b) The change in internal energy is calculated from the first law of thermodynamics

$$\Delta U = Q - W = (1400 \text{ kcal}) \left(\frac{4186 \text{ J}}{1 \text{ kcal}} \right) - 6.262 \times 10^5 \text{ J} = 5.2 \times 10^6 \text{ J}$$

3. 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.

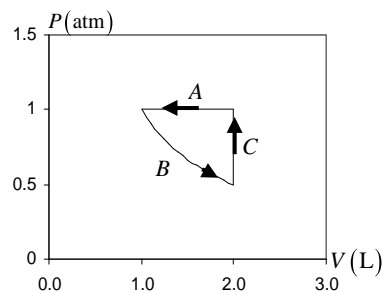
Segment B is the isothermal expansion.



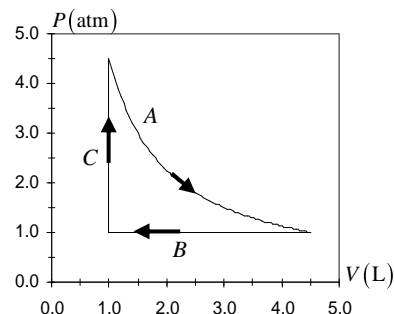
4. Segment A is the compression at constant pressure.

Segment B is the isothermal expansion.

Segment C is the pressure increase at constant volume.



5. Segment A is the isothermal expansion. Since the temperature and the amount of gas are constant, the quantity $PV = nRT$ is constant. Since the pressure is reduced by a factor of 4.5, the volume will increase by a factor of 4.5, to a final volume of 4.5 L.



Segment B is the compression at constant pressure.

Segment C is the pressure increase at constant volume.

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

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

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

$$\Delta U = Q - W = (-265 \text{ kJ}) - 0 = \boxed{-265 \text{ kJ}}$$

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

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

$$\Delta U = Q - W = 0 - (-1850 \text{ J}) = \boxed{1850 \text{ J}}$$

- (c) Since the internal energy is proportional to the temperature, a rise in internal energy means a rise in temperature.

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

$$W = P\Delta V = (3.0 \text{ atm}) \left(\frac{1.01 \times 10^5 \text{ Pa}}{1 \text{ atm}} \right) (660 \times 10^{-3} \text{ L} - 400 \times 10^{-3} \text{ L}) \frac{1 \times 10^{-3} \text{ m}^3}{1 \text{ L}} = \boxed{79 \text{ J}}$$

- (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.

$$\Delta U = Q - W = 0 \rightarrow Q = W = \boxed{79 \text{ J}}$$

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.

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

$$\Delta T = -\frac{2}{3} \frac{W}{nR} = -\frac{2(7500 \text{ J})}{3(1.5 \text{ mol})(8.315 \text{ J/mol}\cdot\text{K})} = -401 \text{ K} = \boxed{-4.0 \times 10^2 \text{ K}}$$

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

$$W = P\Delta V = (1.4 \text{ atm}) \left(\frac{1.01 \times 10^5 \text{ Pa}}{1 \text{ atm}} \right) (9.3 \text{ L} - 6.8 \text{ L}) \frac{1 \times 10^{-3} \text{ m}^3}{1 \text{ L}} = \boxed{3.5 \times 10^2 \text{ J}}$$

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

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

$$\Delta U = Q - W \rightarrow Q = \Delta U + W = 0 + 3.5 \times 10^2 \text{ J} = \boxed{3.5 \times 10^2 \text{ J (into the gas)}}$$

11. (a,c) See diagram.

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

$$W = P\Delta V = (455 \text{ N/m}^2)(8.00 \text{ m}^3 - 2.00 \text{ m}^3)$$

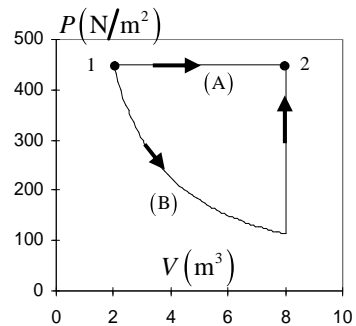
$$= \boxed{2.73 \times 10^3 \text{ J}}$$

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

$$\Delta U = \frac{3}{2}nR\Delta T = \frac{3}{2}(nRT_2 - nRT_1) = \frac{3}{2}[(PV)_2 - (PV)_1]$$

$$= \frac{3}{2}P\Delta V = \frac{3}{2}W = \frac{3}{2}(2.73 \times 10^3 \text{ J}) = \boxed{4.10 \times 10^3 \text{ J}}$$

(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), $\boxed{4.10 \times 10^3 \text{ J}}$.



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

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

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

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

$$\Delta U_{abc} = Q_{abc} - W_{abc} \rightarrow Q_{abc} = \Delta U_{abc} + W_{abc} = -28 \text{ J} + (-48 \text{ J}) = \boxed{-76 \text{ J}}$$

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

$$W_{cda} = W_{cd} = P_c \Delta V_{cd} = P_c (V_d - V_c) = \frac{1}{2} P_b (V_a - V_b) = -\frac{1}{2} W_{abc} = -\frac{1}{2} (-48 \text{ J}) = \boxed{24 \text{ J}}$$

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

$$\Delta U_{cda} = Q_{cda} - W_{cda} \rightarrow Q_{cda} = \Delta U_{cda} + W_{cda} = 28 \text{ J} + 24 \text{ J} = \boxed{52 \text{ J}}$$

(d) As found above, $U_c - U_a = \Delta U_{ca} = -\Delta U_{ac} = \boxed{28 \text{ J}}$

(e) Since $U_d - U_c = 5 \text{ J} \rightarrow U_d = U_c + 5 \text{ J} \rightarrow \Delta U_{da} = U_a - U_d = U_a - U_c - 5 \text{ J} = \Delta U_{ca} - 5 \text{ J} = 23 \text{ J}$.

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

$$\Delta U_{da} = Q_{da} - W_{da} \rightarrow Q_{da} = \Delta U_{da} + W_{da} = 23 \text{ J} + 0 = \boxed{23 \text{ J}}$$

13. We are given that $Q_{ac} = -80 \text{ J}$ and $W_{ac} = -55 \text{ J}$.

(a) Use the first law of thermodynamics to find $U_a - U_c = \Delta U_{ca}$

$$\Delta U_{ca} = -\Delta U_{ac} = -(Q_{ac} - W_{ac}) = -(-80 \text{ J} - (-55 \text{ J})) = \boxed{25 \text{ J}}$$

(b) Use the first law of thermodynamics to find Q_{cda} .

$$\Delta U_{cda} = Q_{cda} - W_{cda} \rightarrow Q_{cda} = \Delta U_{cda} + W_{cda} = \Delta U_{ca} + W_{cda} = 25 \text{ J} + 38 \text{ J} = \boxed{63 \text{ J}}$$

(c) Since the work along path bc is 0, $W_{abc} = W_{ab} = P_a \Delta V_{ab} = P_a (V_b - V_a)$.

$$W_{abc} = W_{ab} = P_a \Delta V_{ab} = P_a (V_b - V_a) = 2.5 P_d (V_c - V_d) = -2.5 W_{cda} = -2.5 (38 \text{ J}) = \boxed{-95 \text{ J}}$$

(d) Use the first law of thermodynamics to find Q_{abc}

$$\Delta U_{abc} = Q_{abc} - W_{abc} \rightarrow Q_{abc} = \Delta U_{abc} + W_{abc} = -25 \text{ J} - 95 \text{ J} = \boxed{-120 \text{ J}}$$

(e) Since $U_a - U_b = 10 \text{ J} \rightarrow U_b = U_a - 10 \text{ J}$, we have the following.

$$\Delta U_{bc} = U_c - U_b = U_c - (U_a - 10 \text{ J}) = \Delta U_{ac} + 10 \text{ J} = -25 \text{ J} + 10 \text{ J} = -15 \text{ J}.$$

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

$$\Delta U_{bc} = Q_{bc} - W_{bc} \rightarrow Q_{bc} = \Delta U_{bc} + W_{bc} = -15 \text{ J} + 0 = \boxed{-15 \text{ J}}$$

14. In Example 15-8, the total energy transformed was $1.15 \times 10^7 \text{ J}$. We will subtract away the energy for 1 hour of desk work and add in the energy for 1 hour of running.

$$\text{Energy} = 1.15 \times 10^7 \text{ J} + [-115 \text{ J/s} + 1150 \text{ J/s}](3600 \text{ s/h}) = \boxed{1.52 \times 10^7 \text{ J}} \approx 3600 \text{ Cal}$$

15. Follow the pattern set in Example 15-8. Find the average rate by dividing the total energy for the day by 24 hours.

$$\text{Avg. Energy} = \frac{\left[(8.0 \text{ h})(70 \text{ J/s}) + (8.0 \text{ h})(115 \text{ J/s}) + (4.0 \text{ h})(230 \text{ J/s}) \right.}{\left. + (2.0 \text{ h})(115 \text{ J/s}) + (1.5 \text{ h})(460 \text{ J/s}) + (0.5 \text{ h})(1150 \text{ J/s}) \right]}{24 \text{ h}} = \boxed{1.62 \times 10^2 \text{ W}}$$

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.

$$\left(160 \frac{\text{J}}{\text{s}} \right) \left(\frac{3600 \text{ s}}{1 \text{ h}} \right) \left(\frac{1 \text{ h}}{\text{day}} \right) \left(\frac{365 \text{ day}}{1 \text{ y}} \right) \left(\frac{1 \text{ kg fat}}{4 \times 10^7 \text{ J}} \right) = 5.256 \text{ kg} \approx \boxed{5.3 \text{ kg}} \left(\frac{2.20 \text{ lb}}{1 \text{ kg}} \right) = \boxed{12 \text{ lbs}}$$

17. The efficiency of a heat engine is given by Eq. 15-4.

$$e = \frac{W}{Q_H} = \frac{W}{W + Q_L} = \frac{3200 \text{ J}}{3200 \text{ J} + 8200 \text{ J}} = 0.28 = \boxed{28\%}$$

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

$$e = \frac{W}{Q_H} = \frac{9200 \text{ J}}{(22.0 \text{ kcal})(4186 \text{ J/kcal})} = 0.10 = \boxed{10\%}$$

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

$$e = 1 - \frac{T_L}{T_H} = 1 - \frac{(380 + 273) \text{ K}}{(580 + 273) \text{ K}} = 0.23 = \boxed{23\%}$$

20. The Carnot efficiency is given by Eq. 15-5, with temperatures in Kelvins.

$$e = 1 - \frac{T_L}{T_H} \rightarrow T_H = \frac{T_L}{1 - e} = \frac{(230 + 273) \text{ K}}{1 - 0.28} = 699 \text{ K} = 426^\circ \text{ C} \approx \boxed{430^\circ \text{ C}}$$

21. The maximum (or Carnot) efficiency is given by Eq. 15-5, with temperatures in Kelvins.

$$e = 1 - \frac{T_L}{T_H} = 1 - \frac{(350 + 273) \text{ K}}{(625 + 273) \text{ K}} = 0.306$$

Thus the total power generated can be found as follows.

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

$$\text{Total Power} = \frac{\text{Actual Power}}{(\text{max. eff.})(\text{operating eff.})} = \frac{1.3 \text{ GW}}{(0.306)(0.75)} = 5.664 \text{ GW}$$

$$\begin{aligned} \text{Exhaust Power} &= \text{Total Power} - \text{Actual Power} = 5.664 \text{ GW} - 1.3 \text{ GW} = 4.364 \text{ GW} \\ &= (4.364 \times 10^9 \text{ J/s})(3600 \text{ s/h}) = \boxed{1.6 \times 10^{13} \text{ J/h}} \end{aligned}$$

22. Calculate the Carnot efficiency for the given temperatures.

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

23. This is a perfect Carnot engine, and so its efficiency is given by Eqs. 15-4 and 15-5. Equate these two expressions for the efficiency.

$$\begin{aligned} e &= 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} \rightarrow \\ T_L &= T_H \left(1 - \frac{W}{Q_H} \right) = T_H \left(1 - \frac{W/t}{Q_H/t} \right) = [(570 + 273) \text{ K}] \left(1 - \frac{4.4 \times 10^5 \text{ J/s}}{(680 \text{ kcal/s})(4186 \text{ J/kcal})} \right) \\ &= 713 \text{ K} = \boxed{440^\circ\text{C}} \end{aligned}$$

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

$$\begin{aligned} e &= 1 - \frac{T_L}{T_H} = 1 - \frac{(45 + 273) \text{ K}}{(210 + 273) \text{ K}} = 0.3416 \quad e = \frac{W}{Q_H} = \frac{W}{W + Q_L} \rightarrow Q_L = W(1/e - 1) \\ Q_L/t &= W/t(1/e - 1) = (950 \text{ W})(1/0.3416 - 1) = \boxed{1.83 \times 10^3 \text{ W}} \end{aligned}$$

25. The efficiency of a heat engine is given by Eq. 15-4.

$$\begin{aligned} e &= \frac{W}{Q_H} = \frac{W}{W + Q_L} \rightarrow Q_L = W(1/e - 1) \rightarrow \\ Q_L/t &= W/t(1/e - 1) = (550 \text{ MW})(1/0.38 - 1) = \boxed{9.0 \times 10^2 \text{ MW}} \end{aligned}$$

26. 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.

$$\begin{aligned} e_1 &= 1 - \frac{T_L}{T_{H1}} \rightarrow T_L = T_{H1}(1 - e) = (550 + 273) \text{ K}(1 - 0.28) = 592.6 \text{ K} \\ e_2 &= 1 - \frac{T_L}{T_{H2}} \rightarrow T_{H2} = \frac{T_L}{1 - e_2} = \frac{592.6 \text{ K}}{1 - 0.35} = 912 \text{ K} = 639^\circ\text{C} \approx \boxed{640^\circ\text{C}} \end{aligned}$$

27. 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.

$$e_1 = 1 - \frac{T_{L1}}{T_H} \rightarrow T_H = \frac{T_{L1}}{1 - e_1} = \frac{(350 + 273) \text{ K}}{1 - 0.39} = 1021 \text{ K}$$

$$e_2 = 1 - \frac{T_{L2}}{T_H} \rightarrow T_{L2} = T_H (1 - e_2) = (1021 \text{ K})(1 - 0.49) = 521 \text{ K} = 248^\circ \text{C} \approx \boxed{250^\circ \text{C}}$$

28. For each engine, the efficiency is given by $e = 0.60e_{\text{Carnot}}$. Thus

$$e_1 = 0.6e_{C-1} = 0.60 \left(1 - \frac{T_{L1}}{T_{H1}} \right) = 0.60 \left[1 - \frac{(440 + 273) \text{ K}}{(670 + 273) \text{ K}} \right] = 0.146$$

$$e_2 = 0.6e_{C-2} = 0.60 \left(1 - \frac{T_{L2}}{T_{H2}} \right) = 0.60 \left[1 - \frac{(290 + 273) \text{ K}}{(430 + 273) \text{ K}} \right] = 0.119$$

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

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

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

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

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 .

$$Q_{\text{coal}}/t = \frac{1100 \times 10^6 \text{ W}}{0.146 + 0.119 - (0.146)(0.119)} = 4.442 \times 10^9 \text{ J/s}$$

$$(4.442 \times 10^9 \text{ J/s}) \left(\frac{1 \text{ kg}}{2.8 \times 10^7 \text{ J}} \right) = 158.6 \text{ kg/s} \approx \boxed{1.6 \times 10^2 \text{ kg/s}}$$

29. The coefficient of performance for a refrigerator is given by Eq. 15-6c, with temperatures in Kelvins.

$$\text{COP} = \frac{T_L}{T_H - T_L} = \frac{(-15 + 273) \text{ K}}{(30 + 273) \text{ K} - (-15 + 273) \text{ K}} = \boxed{5.7}$$

30. The coefficient of performance for a refrigerator is given by Eq. 15-6c, with temperatures in Kelvins.

$$\text{COP} = \frac{T_L}{T_H - T_L} \rightarrow T_L = T_H \left(\frac{\text{COP}}{1 + \text{COP}} \right) = [(24 + 273) \text{ K}] \left(\frac{7.0}{8.0} \right) = 259.9 \text{ K} \approx \boxed{-13^\circ \text{C}}$$

31. The coefficient of performance for a refrigerator is given by Eq. 15-6c, with temperatures in Kelvins. Use that expression to find the temperature inside the refrigerator.

$$\text{COP} = \frac{T_L}{T_H - T_L} \rightarrow T_L = T_H \frac{\text{COP}}{1 + \text{COP}} = [(29 + 273) \text{ K}] \frac{5.0}{6.0} = 252 \text{ K} = \boxed{-21^\circ \text{C}}$$

32. The efficiency of a perfect Carnot engine is given by Eqs. 15-4 and 15-5. Equate these two expressions to solve for the work required.

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

$$(a) \quad W = Q_H \left(1 - \frac{T_L}{T_H} \right) = 2800 \text{ J} \left(1 - \frac{0 + 273}{22 + 273} \right) = \boxed{210 \text{ J}}$$

$$(b) \quad W = Q_H \left(1 - \frac{T_L}{T_H} \right) = 2800 \text{ J} \left(1 - \frac{-15 + 273}{22 + 273} \right) = \boxed{350 \text{ J}}$$

33. The heat to be removed, Q_L , is the latent heat of fusion for the ice, so $Q_L = mL_{\text{fusion}} = V_{\text{H}_2\text{O}} \rho_{\text{H}_2\text{O}} L_{\text{fusion}}$.

The work done in one hour is 1.0 kilowatt-hour. The COP for a refrigerator is $\text{COP} = \frac{Q_L}{W}$, and so

$Q_L = (\text{COP})W$. Equate the two expressions for Q_L and solve for the volume.

$$(\text{COP})W = V_{\text{H}_2\text{O}} \rho_{\text{H}_2\text{O}} L_{\text{fusion}} \rightarrow$$

$$m = \frac{(\text{COP})W}{\rho_{\text{H}_2\text{O}} L_{\text{fusion}}} = \frac{(7.0)(1.0 \times 10^3 \text{ watt} \cdot \text{hour}) \left(\frac{3600 \text{ s}}{1 \text{ hour}} \right) \left(\frac{1 \text{ L}}{1.0 \times 10^{-3} \text{ m}^3} \right)}{(1.00 \times 10^3 \text{ kg/m}^3)(3.33 \times 10^5 \text{ J/kg})} = \boxed{76 \text{ L}}$$

34. The COP for a heat pump is $\text{COP} = \frac{Q_H}{W}$ and the efficiency is $e = \frac{W}{Q_H}$. Thus they are reciprocals of

each other. So if the efficiency is 0.35, the COP is $\frac{1}{0.35} = \boxed{2.9}$.

35. 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.

$$\Delta S = \frac{Q}{T} = -\frac{mL_{\text{vap}}}{T} = -\frac{(0.25 \text{ kg})(22.6 \times 10^5 \text{ J/kg})}{(273 + 100) \text{ K}} = \boxed{-1.5 \times 10^3 \text{ J/K}}$$

36. The heat added to the water is found from $\Delta Q = mc\Delta T$. Use the average temperature of 50°C in the approximate entropy calculation.

$$\Delta S = \frac{Q}{T} = \frac{mc\Delta T}{T} = \frac{(1.00 \text{ kg})(4186 \text{ J/kg}\cdot^\circ\text{C})(100^\circ\text{C})}{(273 + 50) \text{ K}} = \boxed{1.30 \times 10^3 \text{ J/K}}$$

37. Heat energy is taken away from the water, so the change in entropy will be negative. The heat taken away from the water is found from $\Delta Q = mL_{\text{fusion}}$. Note that 1.00 m^3 of water has a mass of

$1.00 \times 10^3 \text{ kg}$.

$$\Delta S = \frac{Q}{T} = -\frac{mL_{\text{fusion}}}{T} = -\frac{(1.00 \times 10^3 \text{ kg})(3.33 \times 10^5 \text{ J/kg})}{273 \text{ K}} = \boxed{-1.22 \times 10^6 \text{ J/K}}$$

38. 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 -10°C , ΔS_2 . That process has an “average” temperature of -5°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.

$$\begin{aligned}\Delta S_1 &= \frac{Q_1}{T_1} = -\frac{mL_{\text{fusion}}}{T_1} = -\frac{(1.00 \times 10^3 \text{ kg})(3.33 \times 10^5 \text{ J/kg})}{273 \text{ K}} = -1.2198 \times 10^6 \text{ J/K} \\ \Delta S_2 &= \frac{Q_2}{T_2} = -\frac{mc_{\text{ice}}\Delta T_2}{T_2} = -\frac{(1.00 \times 10^3 \text{ kg})(2100 \text{ J/kg}\cdot\text{C}^\circ)(10\text{C}^\circ)}{(-5 + 273) \text{ K}} = -7.8358 \times 10^4 \text{ J/K} \\ \Delta S_3 &= \frac{Q_3}{T_3} = \frac{-Q_1 - Q_2}{T_3} = \frac{mL_{\text{fusion}} + mc_{\text{ice}}\Delta T_2}{T_3} \\ &= \frac{(1.00 \times 10^3 \text{ kg})[(3.33 \times 10^5 \text{ J/kg}) + (2100 \text{ J/kg}\cdot\text{C}^\circ)(10\text{C}^\circ)]}{(-10 + 273) \text{ K}} = 1.3460 \times 10^6 \text{ J/K} \\ \Delta S &= \Delta S_1 + \Delta S_2 + \Delta S_3 = -1.2198 \times 10^6 \text{ J/K} - 7.8358 \times 10^4 \text{ J/K} + 1.3460 \times 10^6 \text{ J/K} \\ &= 4.784 \times 10^4 \text{ J/K} \approx \boxed{5 \times 10^4 \text{ J/K}}\end{aligned}$$

39. 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.

$$\Delta S = Q/T = \frac{1}{2}mv_i^2/T = \frac{1}{2}(10.0 \text{ kg})(3.0 \text{ m/s})^2/293 \text{ K} = \boxed{0.15 \text{ J/K}}$$

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

40. 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 .

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

41. The same amount of heat that leaves the high temperature heat source enters the low temperature body of water.

$$\begin{aligned}\Delta S &= \Delta S_1 + \Delta S_2 = -\frac{Q}{T_{\text{high}}} + \frac{Q}{T_{\text{low}}} = Q \left(\frac{1}{T_{\text{low}}} - \frac{1}{T_{\text{high}}} \right) \rightarrow \\ \frac{\Delta S}{t} &= \frac{Q}{t} \left(\frac{1}{T_{\text{low}}} - \frac{1}{T_{\text{high}}} \right) = (7.50 \text{ cal/s}) \left(\frac{4.186 \text{ J}}{1 \text{ cal}} \right) \left(\frac{1}{(27 + 273) \text{ K}} - \frac{1}{(240 + 273) \text{ K}} \right) \\ &= \boxed{4.35 \times 10^{-2} \frac{\text{J/K}}{\text{s}}}\end{aligned}$$

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, 45°C . The cool water average temperature is $(30^\circ\text{C} + 45^\circ\text{C})/2 = 37.5^\circ\text{C}$, and the warm water average temperature is $(60^\circ\text{C} + 45^\circ\text{C})/2 = 52.5^\circ\text{C}$.

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

$$= (1.0 \text{ kg})(4186 \text{ J/kg}\cdot\text{C}^\circ)(15\text{C}^\circ) \left(\frac{1}{(37.5 + 273) \text{ K}} - \frac{1}{(52.5 + 273) \text{ K}} \right) = \boxed{9.3 \text{ J/K}}$$

43. The equilibrium temperature is found using calorimetry, from chapter 14. The heat lost by the aluminum is equal to the heat gained by the water.

$$m_{\text{Al}}c_{\text{Al}}(T_{\text{iAl}} - T_f) = m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}(T_f - T_{\text{iH}_2\text{O}}) \rightarrow$$

$$T_f = \frac{m_{\text{Al}}c_{\text{Al}}T_{\text{iAl}} + m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}T_{\text{iH}_2\text{O}}}{m_{\text{Al}}c_{\text{Al}} + m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}}$$

$$= \frac{(3.8 \text{ kg})(900 \text{ J/kg}\cdot\text{C}^\circ)(30.0^\circ\text{C}) + (1.0 \text{ kg})(4186 \text{ J/kg}\cdot\text{C}^\circ)(20^\circ\text{C})}{(3.8 \text{ kg})(900 \text{ J/kg}\cdot\text{C}^\circ) + (1.0 \text{ kg})(4186 \text{ J/kg}\cdot\text{C}^\circ)} = 24.5^\circ\text{C}$$

The amount of heat lost by the aluminum, and gained by the water, is

$$Q = m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}(T_f - T_{\text{iH}_2\text{O}}) = (1.0 \text{ kg})(4186 \text{ J/kg}\cdot\text{C}^\circ)(24.5^\circ\text{C} - 20^\circ\text{C}) = 1.9 \times 10^4 \text{ J}$$

In calculating the entropy change, we will 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.

$$T_{\text{H}_2\text{O, avg}} = (20^\circ\text{C} + 24.5^\circ\text{C})/2 = 22.25^\circ\text{C} \quad T_{\text{Al, avg}} = (30^\circ\text{C} + 24.5^\circ\text{C})/2 = 27.25^\circ\text{C}$$

$$\Delta S = \Delta S_{\text{Al}} + \Delta S_{\text{H}_2\text{O}} = -\frac{Q}{T_{\text{Al, avg}}} + \frac{Q}{T_{\text{H}_2\text{O, avg}}} = (1.9 \times 10^4 \text{ J}) \left(\frac{1}{(22.25 + 273) \text{ K}} - \frac{1}{(27.25 + 273) \text{ K}} \right) = \boxed{1.1 \text{ J/K}}$$

44. (a) $e_{\text{actual}} = W/Q_H = 550 \text{ J}/2200 \text{ J} = 0.250$ $e_{\text{ideal}} = 1 - T_L/T_H = 1 - 650 \text{ K}/970 \text{ K} = 0.330$

$$\text{Thus } e_{\text{actual}}/e_{\text{ideal}} = 0.250/0.330 = 0.758 \approx \boxed{76\% \text{ of ideal}}$$

- (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 $Q_L = Q_H - W = 2200 \text{ J} - 550 \text{ J} = 1650 \text{ J}$.

$$\Delta S = \Delta S_{\text{input}} + \Delta S_{\text{output}} = -\frac{Q_H}{T_H} + \frac{Q_L}{T_L} = -\frac{2200 \text{ J}}{970 \text{ K}} + \frac{1650 \text{ J}}{650 \text{ K}} = \boxed{0.27 \text{ J/K}}$$

- (c) For the Carnot engine, the exhaust energy will be $Q_L = Q_H(1 - e_{\text{Carnot}}) = Q_H T_L/T_H$.

$$\Delta S = \Delta S_{\text{input}} + \Delta S_{\text{output}} = -\frac{Q_H}{T_H} + \frac{Q_L}{T_L} = -\frac{Q_H}{T_H} + \frac{Q_H T_L/T_H}{T_L} = -\frac{Q_H}{T_H} + \frac{Q_H}{T_H} = \boxed{0}$$

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

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

- (a) The possible microstates that give a total of 5 are: (1)(4), (2)(3), (3)(2), and (4)(1). Thus the probability of getting a 5 is $4/36 = \boxed{1/9}$.

- (b) The possible microstates that give a total of 11 are: (5)(6) and (6)(5). Thus the probability of getting an 11 is $2/36 = \boxed{1/18}$.

46. A macrostate is a set of 5 cards from the deck, as given in the problem. For example, four aces and a king is a macrostate. Two jacks, two queens, and an ace is a macrostate. A microstate is a specific set of cards that meets the criterion of a certain macrostate. For example, the set (ace of spades, ace of clubs, ace of hearts, ace of diamonds, king of spades) is a microstate of the macrostate of 4 aces and a king. The problem then is asking for the relative number of microstates for the 4 given macrostates.
- (a) There are only 4 microstates for this macrostate, corresponding to the particular suit to which the king belongs.
 - (b) Since every card is specified, there is only 1 microstate for this macrostate.
 - (c) There are 6 possible jack pairs, (spade/club, spade/heart, spade/diamond, club/heart, club/diamond, and heart/diamond), 6 possible queen pairs, and 4 possible aces, so there are $6 \times 6 \times 4 = 144$ card combinations or 144 microstates for this macrostate.
 - (d) There are 52 possibilities for the first card, 48 possibilities for the second card, and so on. It is apparent that there are many more microstates for this macrostate than for any of the other listed macrostates.

Thus in order of increasing probability, we have (b), (a), (c), (d).

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

Macrostate	Possible Microstates (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	H H T T 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 H 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		
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		
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 $\frac{20}{64}$.

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

48. The required area is $\left(22 \frac{10^3 \text{ W}\cdot\text{h}}{\text{day}}\right) \left(\frac{1 \text{ day}}{9 \text{ h Sun}}\right) \left(\frac{1 \text{ m}^2}{40 \text{ W}}\right) = 61 \text{ m}^2$. A small house with 1000 ft² of floor

space, and a roof tilted at 30°, would have a roof area of $(1000 \text{ ft}^2) \left(\frac{1}{\cos 30^\circ}\right) \left(\frac{1 \text{ m}}{3.28 \text{ ft}}\right)^2 = 110 \text{ m}^2$,

which is about twice the area needed, and so the cells 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.

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

$$U_{\text{grav}} = mgh = (1.00 \times 10^5 \text{ kg/s})(10.0 \text{ h})(9.80 \text{ m/s}^2)(135 \text{ m}) = 1.323 \times 10^9 \text{ W}\cdot\text{h}$$

$$\approx \boxed{1.32 \times 10^6 \text{ kWh}}$$

(b) $\frac{(1.323 \times 10^6 \text{ kW}\cdot\text{h})(0.75)}{14 \text{ h}} = \boxed{7.1 \times 10^4 \text{ kW}}$

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

$$W = mgh \rightarrow$$

$$P = \frac{W}{t} = \frac{m}{t} gh = \rho \frac{V}{t} gh = (1.00 \times 10^3 \text{ kg/m}^3)(35 \text{ m}^3/\text{s})(9.8 \text{ m/s}^2)(45 \text{ m}) = \boxed{1.5 \times 10^7 \text{ W}}$$

51. According to the heat figures provided by the inventor, the engine is 50% efficient:

$$e = \frac{W}{Q_H} = \frac{W/t}{Q_H/t} = \frac{1.50 \text{ MW}}{3.00 \text{ MW}} = 0.500$$

The ideal engine efficiency at the operating temperatures is given by Eq. 15-5.

$$e_{\text{ideal}} = 1 - \frac{T_L}{T_H} = 1 - \frac{215 \text{ K}}{425 \text{ K}} = 0.494$$

Thus his engine is not possible, even if it were ideal. So yes, there is something “fishy” about his claim. His engine is better than ideal.

52. (a) The work done at constant pressure is $W = P\Delta V$.

$$W = P\Delta V$$

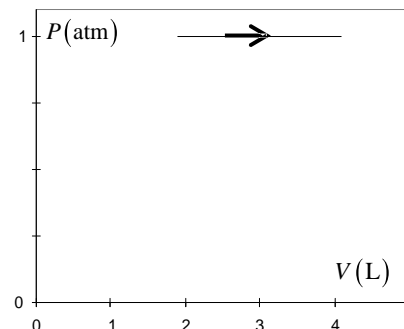
$$= (1.00 \text{ atm})(1.01 \times 10^5 \text{ Pa/atm})(4.1 \text{ m}^3 - 1.9 \text{ m}^3)$$

$$= 2.22 \times 10^5 \text{ J} \approx \boxed{2.2 \times 10^5 \text{ J}}$$

- (b) Use the first law of thermodynamics.

$$\Delta U = Q - W = 5.30 \times 10^5 \text{ J} - 2.22 \times 10^5 \text{ J} = \boxed{3.1 \times 10^5 \text{ J}}$$

- (c) See the adjacent graph.



53. (a) $\text{Work/s} = \left(\frac{220 \text{ J}}{\text{cycle}\cdot\text{cylinder}} \right) \left(\frac{45 \text{ cycles}}{\text{s}} \right) (4 \text{ cylinders}) = 3.96 \times 10^4 \text{ J/s} \approx \boxed{4.0 \times 10^4 \text{ J/s}}$

(b) $e = \frac{W}{Q_H} \rightarrow Q_H = \frac{W}{e} \rightarrow Q_H/t = \frac{W/t}{e} = \frac{3.96 \times 10^4 \text{ J/s}}{0.25} = 1.584 \times 10^5 \text{ J/s} \approx \boxed{1.6 \times 10^5 \text{ J/s}}$

(c) $(1.0 \text{ L}) \left(\frac{35 \times 10^6 \text{ J}}{1 \text{ L}} \right) \left(\frac{1 \text{ s}}{1.584 \times 10^5 \text{ J}} \right) = \boxed{220 \text{ s}} = 3.7 \text{ min}$

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

$$\begin{aligned}
 Q_L &= m(c_{\text{liquid}}\Delta T_{\text{liquid}} + L_{\text{fusion}} + c_{\text{ice}}\Delta T_{\text{ice}}) \\
 &= (0.50 \text{ kg}) \left[(4186 \text{ J/kg}\cdot\text{C}^\circ)(25\text{C}^\circ) + (3.33 \times 10^5 \text{ J/kg}) \right. \\
 &\quad \left. + (2100 \text{ J/kg}\cdot\text{C}^\circ)(17\text{C}^\circ) \right] = 2.367 \times 10^5 \text{ J}
 \end{aligned}$$

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

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

$$W = Q_L \left(\frac{T_H}{T_L} - 1 \right) = (2.367 \times 10^5 \text{ J}) \left(\frac{(25 + 273) \text{ K}}{(-17 + 273) \text{ K}} - 1 \right) = 3.883 \times 10^4 \text{ J} \approx \boxed{3.9 \times 10^4 \text{ J}}$$

- (b) Use the compressor wattage to calculate the time.

$$P = W/t \rightarrow t = W/P = 3.883 \times 10^4 \text{ J} / 210 \text{ W} = 184.9 \text{ s} \approx \boxed{3.1 \text{ min}}$$

55. (a) Calculate the Carnot efficiency for an engine operated between the given temperatures.

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

- (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 “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. 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, and so any changing of surface temperature water might affect at least the local climate, and perhaps also cause larger-scale climate changes.

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.

$$\Delta S = \frac{Q}{T} = \frac{2\left(\frac{1}{2}mv_i^2\right)}{T} = \frac{(1.1 \times 10^3 \text{ kg}) \left[(95 \text{ km/h}) \left(\frac{1 \text{ m/s}}{3.6 \text{ km/h}} \right) \right]^2}{(20 + 273) \text{ K}} = \boxed{2.6 \times 10^3 \text{ J/K}}$$

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.

$$m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}(T_{\text{H}_2\text{O}} - T_f) = m_{\text{Al}}c_{\text{Al}}(T_f - T_{\text{Al}}) \rightarrow$$

$$\begin{aligned}
 T_f &= \frac{m_{\text{Al}}c_{\text{Al}}T_{\text{Al}} + m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}T_{\text{H}_2\text{O}}}{m_{\text{Al}}c_{\text{Al}} + m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}} \\
 &= \frac{(0.12 \text{ kg})(900 \text{ J/kg}\cdot\text{C}^\circ)(15^\circ\text{C}) + (0.14 \text{ kg})(4186 \text{ J/kg}\cdot\text{C}^\circ)(50^\circ\text{C})}{(0.12 \text{ kg})(900 \text{ J/kg}\cdot\text{C}^\circ) + (0.14 \text{ kg})(4186 \text{ J/kg}\cdot\text{C}^\circ)} = 44.55^\circ\text{C} \approx \boxed{45^\circ\text{C}}
 \end{aligned}$$

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

$$Q = m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}(T_{\text{H}_2\text{O}} - T_f) = (0.14 \text{ kg})(4186 \text{ J/kg}\cdot\text{C}^\circ)(50^\circ\text{C} - 44.55^\circ\text{C}) = 3.194 \times 10^3 \text{ J}$$

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.

$$T_{\text{H}_2\text{O, avg}} = (50^\circ\text{C} + 44.55^\circ\text{C})/2 = 47.26^\circ\text{C} \quad T_{\text{Al, avg}} = (15^\circ\text{C} + 44.55^\circ\text{C})/2 = 29.78^\circ\text{C}$$

$$\Delta S = \Delta S_{\text{Al}} + \Delta S_{\text{H}_2\text{O}} = -\frac{Q}{T_{\text{H}_2\text{O, avg}}} + \frac{Q}{T_{\text{Al, avg}}} = (3.194 \times 10^3 \text{ J}) \left(\frac{1}{(29.78 + 273) \text{ K}} - \frac{1}{(47.26 + 273) \text{ K}} \right)$$

$$= 0.5758 \text{ J/K} \approx \boxed{0.58 \text{ J/K}}$$

58. The COP for an ideal heat pump is given by Eq. 15-7.

$$(a) \text{ COP} = \frac{Q_{\text{H}}}{W} = \frac{Q_{\text{H}}}{Q_{\text{H}} - Q_{\text{L}}} = \frac{T_{\text{H}}}{T_{\text{H}} - T_{\text{L}}} = \frac{(24 + 273) \text{ K}}{18 \text{ K}} = 16.5 \approx \boxed{17}$$

$$(b) \text{ COP} = \frac{Q_{\text{H}}}{W} \rightarrow Q_{\text{H}} = (W/t)(t)(\text{COP}) = (1200 \text{ W})(3600 \text{ s})(16.5) = 7.128 \times 10^7 \text{ J} \approx \boxed{7.1 \times 10^7 \text{ J}}$$

59. The efficiency is given by $e = W/Q_{\text{H}} = \frac{W/t}{Q_{\text{H}}/t}$, and so the input power and the useful power are needed.

$$W/t = (25 \text{ hp})(746 \text{ W/hp}) = 1.9 \times 10^4 \text{ J/s}$$

$$Q_{\text{H}}/t = \left(\frac{3.0 \times 10^4 \text{ kcal}}{1 \text{ gal}} \right) \left(\frac{1 \text{ gal}}{41 \text{ km}} \right) \left(\frac{90 \text{ km}}{1 \text{ h}} \right) \left(\frac{4186 \text{ J}}{1 \text{ kcal}} \right) \left(\frac{1 \text{ h}}{3600 \text{ s}} \right) = 7.7 \times 10^4 \text{ J/s}$$

$$e = \frac{W/t}{Q_{\text{H}}/t} = \frac{1.9 \times 10^4 \text{ J/s}}{7.7 \times 10^4 \text{ J/s}} = 0.24 = \boxed{24\%}$$

60. 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.

$$e_1 = 1 - \frac{T_{\text{L}}}{T_{\text{H1}}} \rightarrow T_{\text{H1}} = \frac{T_{\text{L}}}{1 - e_1} \quad e_2 = 1 - \frac{T_{\text{L}}}{T_{\text{H2}}} \rightarrow T_{\text{H2}} = \frac{T_{\text{L}}}{1 - e_2}$$

$$T_{\text{H2}} - T_{\text{H1}} = T_{\text{L}} \left(\frac{1}{1 - e_2} - \frac{1}{1 - e_1} \right) = (273 \text{ K} + 20 \text{ K}) \left(\frac{1}{0.60} - \frac{1}{0.70} \right) = \boxed{70 \text{ K}}$$

61. 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.

$$(a) W_{\text{ADC}} = \boxed{P_{\text{A}}(V_{\text{C}} - V_{\text{A}})}$$

$$(b) W_{\text{ABC}} = \boxed{P_{\text{C}}(V_{\text{C}} - V_{\text{A}})}$$

$$(c) W_{\text{AC}} = \boxed{\frac{1}{2}(P_{\text{C}} + P_{\text{A}})(V_{\text{C}} - V_{\text{A}})}$$

62. (a) The exhaust heating rate is found from the delivered power and the efficiency. Use the output energy with the relationship $Q = mc\Delta T = \rho Vc\Delta T$ to calculate the volume of air that is heated.

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

$$Q_L/t = W/t(1/e - 1) = (8.5 \times 10^8 \text{ W})(1/0.33 - 1) = 1.726 \times 10^9 \text{ W}$$

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

The change in air temperature is 7.0°C . The heated air is at a constant pressure of 1 atm.

$$V/t = \frac{(Q_L/t)t}{\rho c\Delta T} = \frac{(1.726 \times 10^9 \text{ W})(8.64 \times 10^4 \text{ s/day})}{(1.2 \text{ kg/m}^3)(1.0 \times 10^3 \text{ J/kg}\cdot^\circ\text{C})(7.0^\circ\text{C})}$$

$$= 1.775 \times 10^{10} \text{ m}^3/\text{day} \left(\frac{10^{-9} \text{ km}^3}{1 \text{ m}^3} \right) \approx \boxed{18 \text{ km}^3/\text{day}}$$

- (b) If the air is 200 m thick, find the area by dividing the volume by the thickness.

$$A = \frac{\text{Volume}}{\text{thickness}} = \frac{18 \text{ km}^3}{0.2 \text{ km}} = \boxed{90 \text{ km}^2}$$

This would be a square of approximately 6 miles to a side. Thus the local climate for a few miles around the power plant might be heated significantly.

63. (a) The exhaust heating rate can be found from the delivered power P and the Carnot efficiency. Then use the relationship between energy and temperature change, $Q = mc\Delta T$, to calculate the temperature change of the cooling water.

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

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

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

$$P \frac{T_L}{T_H - T_L} = \rho \frac{V}{t} c\Delta T \rightarrow \Delta T = \frac{P}{\rho \frac{V}{t} c} \frac{T_L}{T_H - T_L}$$

$$= \frac{9.8 \times 10^8 \text{ W}}{(1.0 \times 10^3 \text{ kg/m}^3)(37 \text{ m}^3/\text{s})(4186 \text{ J/kg}\cdot^\circ\text{C})} \frac{285 \text{ K}}{(625 \text{ K} - 285 \text{ K})} = 5.303 \text{ K} = \boxed{5.3^\circ\text{C}}$$

- (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.

$$\Delta S = \frac{\Delta Q}{T} = \frac{c\Delta T}{T_0 + \frac{1}{2}\Delta T} = \frac{(4186 \text{ J/kg}\cdot^\circ\text{C})(5.303 \text{ K})}{[285 + \frac{1}{2}(5.303)] \text{ K}} = \boxed{77 \text{ J/kg}\cdot\text{K}}$$

64. (a) Calculate the Carnot efficiency by $e = 1 - T_L/T_H$ and compare it to the 15% actual efficiency.

$$e_{\text{Carnot}} = 1 - T_L/T_H = 1 - (85 + 273) \text{ K} / (495 + 273) \text{ K} = 0.534 = 53.4\%$$

Thus the engine's relative efficiency is $e_{\text{actual}}/e_{\text{Carnot}} = 0.15/0.534 = 0.281 = \boxed{28\%}$

- (b) Take the stated 100 hp as the useful power obtained from the engine. Use the efficiency to calculate the exhaust heat.

$$P = \frac{W}{t} = (100 \text{ hp}) \left(\frac{746 \text{ W}}{1 \text{ hp}} \right) = \boxed{7.46 \times 10^4 \text{ W}}$$

$$e = \frac{W}{Q_H} = \frac{W}{Q_L + W} \rightarrow$$

$$Q_L = W \left(\frac{1}{e} - 1 \right) = Pt \left(\frac{1}{e} - 1 \right) = (7.46 \times 10^4 \text{ J/s})(1 \text{ h}) \left(\frac{3600 \text{ s}}{1 \text{ h}} \right) \left(\frac{1}{0.15} - 1 \right)$$

$$= \boxed{1.5 \times 10^9 \text{ J}} = (1.5 \times 10^9 \text{ J}) \left(\frac{1 \text{ kcal}}{4186 \text{ J}} \right) = \boxed{3.6 \times 10^5 \text{ kcal}}$$

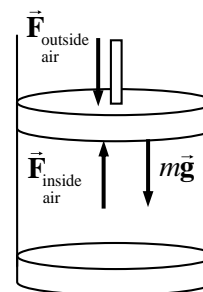
65. The net force on the piston must be 0, and so the weight of the piston must be equal to the net force exerted by the gas pressures on both sides of the piston. See the free-body diagram.

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

$$P_{\text{inside}} = P_{\text{outside}} + \frac{mg}{A} = (1.0 \text{ atm}) \left(1.01 \times 10^5 \frac{\text{Pa}}{\text{atm}} \right) + \frac{(0.10 \text{ kg})(9.8 \text{ m/s}^2)}{0.080 \text{ m}^2}$$

$$= 1.0101 \times 10^5 \text{ Pa} \approx 1 \text{ atm}$$

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, and so the work done can be calculated. Use this with the first law of thermodynamics to find the heat required for the process.

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

$$Q = \Delta U + W = \frac{3}{2} P\Delta V + P\Delta V = \frac{5}{2} P\Delta V = \frac{5}{2} PA\Delta y = 2.5(1.0 \times 10^5 \text{ Pa})(0.080 \text{ m}^2)(1.0 \times 10^{-2} \text{ m})$$

$$= \boxed{200 \text{ J}}$$

66. (a) Multiply the power times the time times the mass per Joule relationship for the fat.

$$(95 \text{ J/s})(3600 \text{ s/h})(24 \text{ h/d})(1.0 \text{ kg fat}/3.7 \times 10^7 \text{ J}) = 0.2218 \text{ kg/d} \approx \boxed{0.22 \text{ kg/d}}$$

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

67. The radiant energy is the heat to be removed at the low temperature. It can be related to the work necessary through the efficiency.

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

$$(W/t)_{5300} = (5300 \text{ W}) \left(\frac{T_H}{T_L} - 1 \right) \quad (W/t)_{500} = (500 \text{ W}) \left(\frac{T_H}{T_L} - 1 \right)$$

$$(W/t)_{\text{savings}} = (W/t)_{5300} - (W/t)_{500} = (5300 \text{ W} - 500 \text{ W}) \left(\frac{(273 + 32) \text{ K}}{(273 + 21) \text{ K}} - 1 \right) = \boxed{180 \text{ W}}$$

68. 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.

$$e = 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} = \frac{W}{W + Q_L} \rightarrow Q_L = W \frac{T_L}{(T_H - T_L)} = mL_{\text{vapor}}$$

$$m = \frac{W}{L_{\text{vapor}}} \frac{T_L}{(T_H - T_L)} = \frac{(600 \text{ W})(3600 \text{ s})(273 + 8) \text{ K}}{(2.45 \times 10^6 \text{ J/kg}) 17 \text{ K}} = \boxed{14.6 \text{ kg}}$$