Chapter 22 Solutions

22.1 (a) $e = \frac{W}{Q_h} = \frac{25.0\text{ J}}{360\text{ J}} = \boxed{0.0694}$ or $\boxed{6.94\%}$

(b) $Q_c = Q_h - W = 360\text{ J} - 25.0\text{ J} = \boxed{335\text{ J}}$

22.2 (a) $e = \frac{W}{Q_h} = \frac{W}{3W} = \frac{1}{3} = \boxed{0.333}$ or $\boxed{33.3\%}$

(b) $Q_c = Q_h - W = 3W - W = 2W$

Therefore, $\frac{Q_c}{Q_h} = \frac{2W}{3W} = \boxed{\frac{2}{3}}$

22.3 (a) We have $e = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h} = 0.250,$

with $Q_c = 8000$ J, we have $Q_h = \boxed{10.7\text{ kJ}}$

(b) $W = Q_h - Q_c = 2667\text{ J}$

and from $\wp = \frac{W}{t}$, we have $t = \frac{W}{\wp} = \frac{2667\text{ J}}{5000\text{ J/s}} = \boxed{0.533\text{ s}}$

22.4 $W = Q_h - Q_c = 200\text{ J}$ (1)

$e = \frac{W}{Q_h} = 1 - \frac{Q_c}{Q_h} = 0.300$ (2)

From (2), $Q_c = 0.700Q_h$(3)

Solving (3) and (1) simultaneously, we have

$\boxed{Q_h = 667\text{ J}}$ and $\boxed{Q_c = 467\text{ J}}$

22.5 It is easiest to solve part (b) first:

(b) $\Delta E_{\text{int}} = nC_V\,\Delta T$ and since the temperature is held constant during the compression, $\Delta E_{\text{int}} = \boxed{0}$.

(a) From the first law of thermodynamics, $\Delta E_{\text{int}} = Q - W$.

Since $\Delta E_{\text{int}} = 0$, this gives: $W = Q = 1000\text{ J} = \boxed{1.00\text{ kJ}}$

22.6 Q_c = heat to melt 15.0 g of Hg $= mL_f = (15.0 \times 10^{-3}\text{ kg})(1.18 \times 10^4\text{ J/kg}) = 177\text{ J}$

Q_h = heat absorbed to freeze 1.00 g of aluminum

$= mL_f = (10^{-3}\text{ kg})(3.97 \times 10^5\text{ J/kg}) = 397\text{ J}$

and the work output $= W = Q_h - Q_c = 220\text{ J}$

$$e = \frac{W}{Q_h} = \frac{220\text{ J}}{397\text{ J}} = 0.554\text{, or } \boxed{55.4\%}$$

$$\left[\text{Theoretical Eff (Carnot)} = \left(\frac{T_h}{T_h - T_c}\right) = \frac{933\text{ K} - 243.1\text{ K}}{933\text{ K}} = 0.749 = 74.9\%\right]$$

22.7 $T_c = 703\text{ K}$, $T_h = 2143\text{ K}$

(a) $$e_C = \frac{\Delta T}{T_h} = \frac{1440}{2143} = \boxed{67.2\%}$$

(b) $Q_h = 1.40 \times 10^5\text{ J}$, $W = 0.420 Q_h$

$$\wp = \frac{W}{t} = \frac{5.88 \times 10^4\text{ J}}{1\text{ s}} = \boxed{58.8\text{ kW}}$$

***22.8** The Carnot efficiency of the engine is

$$e_C = \frac{\Delta T}{T_h} = \frac{120\text{ K}}{473\text{ K}} = 0.253$$

At 20.0% of this maximum efficiency,

$$e = (0.200)(0.253) = 0.0506$$

From Equation 22.2,

$$W = Q_h e \quad\text{and}\quad Q_h = \frac{W}{e} = \frac{10.0\text{ kJ}}{0.0506} = \boxed{197\text{ kJ}}$$

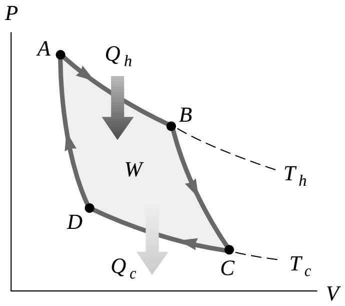
22.9 When $e = e_C$, $1 - \dfrac{T_c}{T_h} = \dfrac{W}{Q_h}$, and $\dfrac{\left(\frac{W}{t}\right)}{\left(\frac{Q_h}{t}\right)} = 1 - \dfrac{T_c}{T_h}$

(a) $$Q_h = \frac{(W/t)t}{1 - (T_c/T_h)} = \frac{(1.50 \times 10^5\text{ W})(3600\text{ s})}{1 - (293/773)}$$

$$Q_h = 8.69 \times 10^8\text{ J} = \boxed{869\text{ MJ}}$$

(c) $$Q_c = Q_h - \left(\frac{W}{t}\right)t = 8.69 \times 10^8 - (1.50 \times 10^5)(3600) = 3.30 \times 10^8\text{ J} = \boxed{330\text{ MJ}}$$

22.10 From Equation 22.4,



(a) $e_C = \dfrac{\Delta T}{T_h} = \dfrac{100}{373} = 0.268 = \boxed{26.8\%}$

(b) $e_C = \dfrac{\Delta T}{T_h} = \dfrac{200}{473} = 0.423 = \boxed{42.3\%}$

***22.11** Isothermal expansion at $T_h = 523$ K

Isothermal compression at $T_c = 323$ K

Gas absorbs 1200 J during expansion.

(a) $Q_c = Q_h \dfrac{T_c}{T_h} = (1200\text{ J})\left(\dfrac{323}{523}\right) = \boxed{741\text{ J}}$

(b) $W = Q_h - Q_c = (1200 - 741)\text{ J} = \boxed{459\text{ J}}$

***22.12** We use $e_C = 1 - \dfrac{T_c}{T_h}$

as, $0.300 = 1 - \dfrac{573\text{ K}}{T_h}$

From which, $T_h = 819\text{ K} = \boxed{546°\text{C}}$

22.13 The Carnot summer efficiency is

$$e_{C,s} = 1 - \frac{T_c}{T_h} = 1 - \frac{(273 + 20)\text{K}}{(273 + 350)\text{K}} = 0.530$$

And in winter, $e_{C,w} = 1 - \dfrac{283}{623} = 0.546$

Then the actual winter efficiency is

$$0.320\left(\frac{0.546}{0.530}\right) = \boxed{0.330} \quad \text{or} \quad \boxed{33.0\%}$$

***22.14** (a) In an adiabatic process, $P_f V_f^{\gamma} = P_i V_i^{\gamma}$. Also, $\left(\frac{P_f V_f}{T_f}\right)^{\gamma} = \left(\frac{P_i V_i}{T_i}\right)^{\gamma}$

Dividing the second equation by the first yields $T_f = T_i \left(\frac{P_f}{P_i}\right)^{(\gamma-1)/\gamma}$

Since $\gamma = \frac{5}{3}$ for Argon, $\frac{\gamma - 1}{\gamma} = \frac{2}{5} = 0.400$ and we have

$$T_f = (1073\text{ K})\left(\frac{300 \times 10^3\text{ Pa}}{1.50 \times 10^6\text{ Pa}}\right)^{0.400} = \boxed{564\text{ K}}$$

(b) $\Delta E_{\text{int}} = nC_V\,\Delta T = Q - W = 0 - W$, so $W = -nC_V\,\Delta T$,

and the power output is

$$\wp = \frac{W}{t} = \frac{-nC_V\,\Delta T}{t} \quad \text{or}$$

$$= \frac{(-80.0\text{ kg})(1.00\text{ mol}/0.0399\text{ kg})(3/2)(8.315\text{ J/mol}\cdot\text{K})(564 - 1073)\text{ K}}{60.0\text{ s}}$$

$$\wp = 2.12 \times 10^5\text{ W} = \boxed{212\text{ kW}}$$

(c) $e_C = 1 - \frac{T_c}{T_h} = 1 - \frac{564\text{ K}}{1073\text{ K}} = 0.475 \quad \text{or} \quad \boxed{47.5\%}$

22.15 (a) $e_{\max} = 1 - \frac{T_c}{T_h} = 1 - \frac{278}{293} = 5.12 \times 10^{-2} = \boxed{5.12\%}$

(b) $\wp = \frac{W}{t} = 75.0 \times 10^6\text{ J/s}$

Therefore, $W = (75.0 \times 10^6\text{ J/s})(3600\text{ s/h}) = 2.70 \times 10^{11}\text{ J/h}$

From $e = \frac{W}{Q_h}$, we find

$$Q_h = \frac{W}{e} = \frac{2.70 \times 10^{11}\text{ J/h}}{5.12 \times 10^{-2}} = 5.27 \times 10^{12}\text{ J/h} = \boxed{5.27\text{ TJ/h}}$$

(c) As fossil-fuel prices rise, this way to use solar energy will become a good buy.

22.16 The work output is $W = \frac{1}{2}\, m_{\text{train}}\,(5.00\ \text{m/s})^2$

We are told $e = \frac{W}{Q_h}$

$$0.200 = \frac{1}{2}\, m_t\,(5.00\ \text{m/s})^2 / Q_h$$

and $e_{\text{C}} = 1 - \frac{300\ \text{K}}{T_h} = \frac{1}{2}\, m_t\,(6.50\ \text{m/s})^2 / Q_h$

Substitute $Q_h = \frac{1}{2}\, m_t\,(5.00\ \text{m/s})^2 / 0.200$

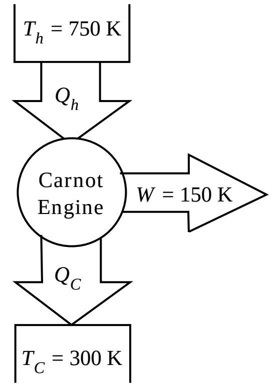
Then, $1 - \frac{300\ \text{K}}{T_h} = 0.200\left(\frac{\frac{1}{2} m_t\,(6.50\ \text{m/s})^2}{\frac{1}{2} m_t\,(5.00\ \text{m/s})^2}\right)$

$$1 - \frac{300\ \text{K}}{T_h} = 0.338$$

$$T_h = \frac{300\ \text{K}}{0.662} = \boxed{453\ \text{K}}$$

***22.17** For the Carnot engine,

$$e_C = 1 - \frac{T_c}{T_h} = 1 - \frac{300\ \text{K}}{750\ \text{K}} = 0.600$$



Also, $e_C = \frac{W}{Q_h}$, so $Q_h = \frac{W}{e_{\text{C}}} = \frac{150\ \text{J}}{0.600} = 250\ \text{J}$

and $Q_c = Q_h - W = 250\ \text{J} - 150\ \text{J} = 100\ \text{J}$

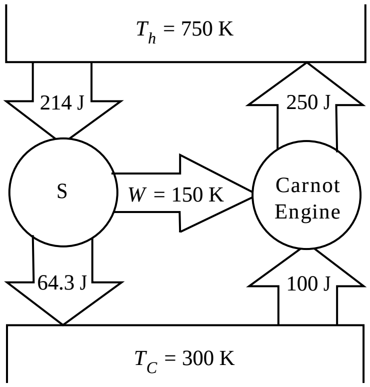
(a) $Q_h = \frac{W}{e_{\text{S}}} = \frac{150\ \text{J}}{0.700} = \boxed{214\ \text{J}}$

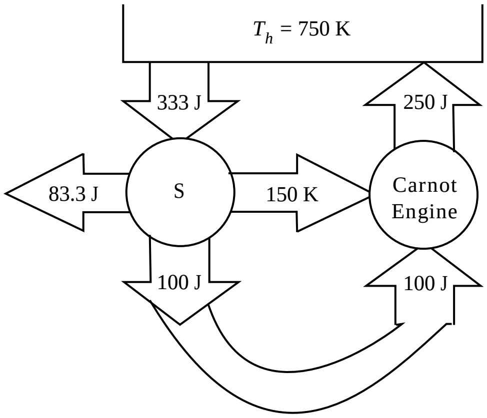
$$Q_c = Q_h - W = 214\ \text{J} - 150\ \text{J} = \boxed{64.3\ \text{J}}$$

(b) $Q_{h,\text{net}} = 214\ \text{J} - 250\ \text{J} = \boxed{-35.7\ \text{J}}$

$$Q_{c,\text{net}} = 64.3\ \text{J} - 100\ \text{J} = \boxed{-35.7\ \text{J}}$$

The flow of net heat from the cold to the hot reservoir, without work input, is impossible.





(c) For engine S: $Q_c = Q_h - W = \dfrac{W}{e_s} - W$, so

$$W = \frac{Q_c}{1/e_s - 1} = \frac{100\text{ J}}{(1/0.700) - 1} = \boxed{233\text{ J}}$$

and $Q_h = Q_c + W = 233\text{ J} + 100\text{ J} = \boxed{333\text{ J}}$

(d) $Q_{h,\text{net}} = 333\text{ J} - 250\text{ J} = \boxed{83.3\text{ J}}$

$W_{\text{net}} = 233\text{ J} - 150\text{ J} = \boxed{83.3\text{ J}}$

$Q_{c,\text{ net}} = \boxed{0}$

The conversion of 83.3 J of heat entirely into work, without heat exhaust, is impossible.

(e) Both engines operate in cycles, so

$$\Delta S_s = \Delta S_{\text{Carnot}} = 0$$

For the reservoirs, $\Delta S_h = -\dfrac{Q_h}{T_h}$ and $\Delta S_c = +\dfrac{Q_c}{T_c}$

Thus,

$$\Delta S_{\text{total}} = \Delta S_s + \Delta S_{\text{Carnot}} + \Delta S_h + \Delta S_c = 0 + 0 - \frac{83.3\text{ J}}{750\text{ K}} + \frac{0}{300\text{ K}} = \boxed{-0.111\text{ J/K}}$$

A decrease in total entropy is impossible.

22.18 (a) First, consider the adiabatic process $D \to A$:

$$P_D V_D^\gamma = P_A V_A^\gamma \quad \text{so} \quad P_D = P_A\left(\frac{V_A}{V_D}\right)^\gamma = 1400\text{ kPa}\left(\frac{10.0\text{ L}}{15.0\text{ L}}\right)^{5/3} = \boxed{712\text{ kPa}}$$

Also, $\left(\dfrac{nRT_D}{V_D}\right) V_D^\gamma = \left(\dfrac{nRT_A}{V_A}\right) V_A^\gamma$, or

$$T_D = T_A\left(\frac{V_A}{V_D}\right)^{\gamma - 1} = (720\text{ K})\left(\frac{10.0}{15.0}\right)^{2/3} = \boxed{549\text{ K}}$$

Now, consider the isothermal process $C \to D$:

$$T_C = T_D = \boxed{549\text{ K}}$$

$$P_C = P_D\left(\frac{V_D}{V_C}\right) = \left[P_A\left(\frac{V_A}{V_D}\right)^{\gamma}\right]\left(\frac{V_D}{V_C}\right) = \frac{P_A V_A^{\gamma}}{V_C V_D^{\gamma-1}}$$

$$P_C = \frac{(1400\text{ kPa})(10.0\text{ L})^{5/3}}{(24.0\text{ L})(15.0\text{ L})^{2/3}} = \boxed{445\text{ kPa}}$$

Next, consider the adiabatic process $B \to C$:

$$P_B V_B^{\gamma} = P_C V_C^{\gamma}$$

But, $P_C = \dfrac{P_A V_A^{\gamma}}{V_C V_D^{\gamma-1}}$ from above. Also, considering the isothermal process, $P_B = P_A\left(\dfrac{V_A}{V_B}\right)$. Hence, $P_A\left(\dfrac{V_A}{V_B}\right) V_B^{\gamma} = \left(\dfrac{P_A V_A^{\gamma}}{V_C V_D^{\gamma-1}}\right) V_C^{\gamma}$ which reduces to $V_B = \dfrac{V_A V_C}{V_D} = \dfrac{(10.0\text{ L})(24.0\text{ L})}{15.0\text{ L}} = \boxed{16.0\text{ L}}$

Finally, $P_B = P_A\left(\dfrac{V_A}{V_B}\right) = (1400\text{ kPa})\left(\dfrac{10.0\text{ L}}{16.0\text{ L}}\right) = \boxed{875\text{ kPa}}$

State	P(kPa)	V(L)	T(K)
A	1400	10.0	720
B	875	16.0	720
C	445	24.0	549
D	712	15.0	549

(b) For the isothermal process $A \to B$:

$$\Delta E_{\text{int}} = nC_V\,\Delta T = \boxed{0}$$

so $$Q = W = nRT\ln\left(\frac{V_B}{V_A}\right) = (2.34\text{ mol})(8.315\text{ J/mol}\cdot\text{K})(720\text{ K})\ln\left(\frac{16.0}{10.0}\right)$$

$$Q = W = \boxed{+6.58\text{ kJ}}$$

For the adiabatic process $B \to C$:

$$Q = \boxed{0}$$

$$\Delta E_{\text{int}} = nC_V(T_C - T_B) = (2.34 \text{ mol})\left[\frac{3}{2}\left(8.315 \frac{\text{J}}{\text{mol} \cdot \text{K}}\right)\right](549 - 720) = \boxed{-4.99 \text{ kJ}}$$

and $W = Q - \Delta E_{\text{int}} = 0 - (-4.99 \text{ kJ}) = \boxed{+4.99 \text{ kJ}}$

For the isothermal process $C \to D$:

$$\Delta E_{\text{int}} = nC_V\,\Delta T = \boxed{0}$$

and $Q = W = nRT \ln\left(\frac{V_D}{V_C}\right) = (2.34 \text{ mol})(8.315 \text{ J/mol} \cdot \text{K})(549 \text{ K}) \ln\left(\frac{15.0}{24.0}\right)$

$$Q = W = \boxed{-5.02 \text{ kJ}}$$

Finally, for the adiabatic process $D \to A$:

$$Q = \boxed{0}$$

$$\Delta E_{\text{int}} = nC_V(T_A - T_D) = (234 \text{ mol})\left[\frac{3}{2}\left(8.315 \frac{\text{J}}{\text{mol} \cdot \text{K}}\right)\right](720 - 549) = \boxed{+4.99 \text{ kJ}}$$

and $W = Q - \Delta E_{\text{int}} = 0 - (+4.99 \text{ kJ}) = \boxed{-4.99 \text{ kJ}}$

Process	Q(kJ)	W(kJ)	ΔE_{int}(kJ)
$A \to B$	+6.58	+6.58	0
$B \to C$	0	+4.99	−4.99
$C \to D$	−5.02	−5.02	0
$D \to A$	0	−4.99	+4.99
$ABCDA$	+1.56	+1.56	0

(c) $e = \frac{W_{\text{net}}}{Q_h} = \frac{W_{ABCDA}}{Q_{A \to B}} = \frac{1.56 \text{ kJ}}{6.58 \text{ kJ}} = 0.237$ or $\boxed{23.7\%}$

$$e_C = 1 - \frac{T_c}{T_h} = 1 - \frac{549}{720} = 0.237 \quad \text{or} \quad \boxed{23.7\%}$$

22.19 (a) $P_i V_i^{\gamma} = P_f V_f^{\gamma}$

$$P_f = P_i\left(\frac{V_i}{V_f}\right)^{\gamma} = (3.00 \times 10^6 \text{ Pa})\left(\frac{50.0 \text{ cm}^3}{300 \text{ cm}^3}\right)^{1.40} = \boxed{244 \text{ kPa}}$$

(b) $W = \int_{V_i}^{V_i} P\,dV \qquad P = P_i\left(\frac{V_i}{V}\right)^{\gamma}$

Integrating,

$$W = \left(\frac{1}{\gamma - 1}\right) P_i V_i\left[1 - \left(\frac{V_i}{V_f}\right)^{\gamma - 1}\right]$$

$$= (2.50)(3.00 \times 10^6\ \text{Pa})(5.00 \times 10^{-5}\ \text{m}^3)\left[1 - \left(\frac{50.0\ \text{cm}^3}{300\ \text{cm}^3}\right)^{0.400}\right]\ \text{J} = \boxed{192\ \text{J}}$$

Goal Solution

G: The pressure will decrease as the volume increases, so a reasonable estimate of the final pressure might be $P_f \approx \frac{50}{300}(3 \times 10^6\ \text{Pa}) = 5 \times 10^5$ Pa. As the gas expands, it does work on the piston, so $W > 0$, and the amount of work can be estimated from the average pressure and volume: $W \sim (10^6\ \text{N/m}^2)(100\ \text{cm}^3)(1\ \text{m}^3/10^6\ \text{cm}^3) = 100$ J

O: The gas expands adiabatically (there is not enough time for significant heat transfer), so equation 21.18 can be applied to find the final pressure. With $Q = 0$, the amount of work can be found from the change in internal energy.

A: (a) For adiabatic expansion, $P_i V_i^{\gamma} = P_f V_f^{\gamma}$

Therefore, $P_f = P_i\left(\frac{V_i}{V_f}\right)^{\gamma} = 3.0 \times 10^6\ \text{Pa}\left(\frac{50\ \text{cm}^3}{300\ \text{cm}^3}\right)^{1.40} = 2.44 \times 10^5\ \text{Pa}$

(b) Since $Q = 0$, we have $W = Q - \Delta E_{\text{int}} = -\Delta E_{\text{int}} = -nC_V\Delta T = -nC_V(T_f - T_i)$

From $\gamma = \frac{C_P}{C_v} = \frac{C_V + R}{C_v}$, we get $(\gamma - 1)C_V = R$

So that $C_V = \frac{R}{1.40 - 1} = 2.5R$

Therefore, $W = n(2.5R)(T_i - T_f) = 2.5P_iV_i - 2.5P_fV_f$

$$W = 2.5(3 \times 10^6\ \text{Pa})(50 \times 10^{-6}\ \text{m}^3) - (2.5)(2.44 \times 10^5\ \text{Pa})(300 \times 10^{-6}\ \text{m}^3) = 192\ \text{J}$$

L: The final pressure is about half what we predicted because we assumed a linear proportionality ($\gamma = 1$) in our initial estimate, when in fact $\gamma = 1.40$. The work done is about twice what we predicted, and the difference is again because our estimate assumed a linear relationship when this is not the case.
From the work done by the gas in part (a), the average power (horsepower) of the engine could be calculated if the time for one cycle was known. Adiabatic expansion is the power stroke of our industrial civilization!

22.20 Compression ratio = 6.00, $\gamma = 1.40$

(a) Efficiency of an Otto-engine $e = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma - 1}$

$$e = 1 - \left(\frac{1}{6.00}\right)^{0.400} = \boxed{51.2\%}$$

(b) If actual efficiency $e' = 15.0\%$ losses in system are $e - e' = \boxed{36.2\%}$

22.21 $e_{\text{Otto}} = 1 - \frac{1}{(V_1/V_2)^{\gamma-1}} = 1 - \frac{1}{(6.20)^{(7/5-1)}} = 1 - \frac{1}{(6.20)^{0.400}}$

$e_{\text{Otto}} = 0.518$

We have assumed the fuel-air mixture to behave like a diatomic gas.

Now $e = W/Q_h = (W/t)/(Q_h/t)$

$Q_h/t = (W/t)/e = 102\text{ hp }(746\text{ W}/1\text{ hp})/0.518$

$Q_h/t = \boxed{146\text{ kW}}$

$Q_h = W + Q_c$

$Q_c/t = Q_h/t - W/t$

$Q_h/t = 146 \times 10^3\text{ W} - 102\text{ hp}(746\text{ W}/1\text{ hp}) = \boxed{70.8\text{ kW}}$

***22.22** (a) and (b) The quantity of gas is

$$n = \frac{P_A V_A}{R T_A} = \frac{(100 \times 10^3\text{ Pa})(500 \times 10^{-6}\text{ m}^3)}{(8.315\text{ J/mol}\cdot\text{K})(293\text{ K})} = 0.0205\text{ mol}$$

$$E_{\text{int},A} = \frac{5}{2} nRT_A = \frac{5}{2} P_A V_A = \frac{5}{2}(100 \times 10^3\text{ Pa})(500 \times 10^{-6}\text{ m}^3) = \boxed{125\text{ J}}$$

In process AB, $P_B = P_A \left(\frac{V_A}{V_B}\right)^{\gamma} = (100 \times 10^3\text{ Pa})(8.00)^{1.40} = \boxed{1.84 \times 10^6\text{ Pa}}$

$$T_B = \frac{P_B V_B}{nR} = \frac{(100 \times 10^3\text{ Pa})(500 \times 10^{-6}\text{ m}^3/8.00)}{(0.0205\text{ mol})(8.315\text{ J/mol}\cdot\text{K})} = \boxed{673\text{ K}}$$

$$E_{\text{int},B} = \frac{5}{2} nRT_B = \frac{5}{2}(0.0205\text{ mol})(8.315\text{ J/mol}\cdot\text{K})(673\text{ K}) = \boxed{287\text{ J}}$$

so $\Delta E_{\text{int},AB} = 287\text{ J} - 125\text{ J} = \boxed{162\text{ J}} = Q - W = 0 - W \qquad W_{AB} = \boxed{-162\text{ J}}$

Process BC takes us to:

$$P_C = \frac{nRT_C}{V_C} = \frac{(0.0205\text{ mol})(8.315\text{ J/mol}\cdot\text{K})(1023\text{ K})}{62.5\times10^{-6}\text{ m}^3} = \boxed{2.79\times10^{6}\text{ Pa}}$$

$$E_{\text{int},C} = \frac{5}{2}nRT_C = \frac{5}{2}(0.0205\text{ mol})(8.315\text{ J/mol}\cdot\text{K})(1023\text{ K}) = \boxed{436\text{ J}}$$

$$\Delta E_{\text{int},BC} = 436\text{ J} - 287\text{ J} = \boxed{149\text{ J}} = Q - W = Q - 0 \qquad Q_{BC} = \boxed{149\text{ J}}$$

In process CD:

$$P_D = P_C\left(\frac{V_C}{V_D}\right)^{\gamma} = (2.79\times10^{6}\text{ Pa})\left(\frac{1}{8.00}\right)^{1.40} = \boxed{1.52\times10^{5}\text{ Pa}}$$

$$T_D = \frac{P_DV_D}{nR} = \frac{(1.52\times10^{5}\text{ Pa})(500\times10^{-6}\text{ m}^3)}{(0.0205\text{ mol})(8.315\text{ J/mol}\cdot\text{K})} = \boxed{445\text{ K}}$$

$$E_{\text{int},D} = \frac{5}{2}nRT_D = \frac{5}{2}(0.0205\text{ mol})(8.315\text{ J/mol}\cdot\text{K})(445\text{ K}) = \boxed{190\text{ J}}$$

$$\Delta E_{\text{int},CD} = 190\text{ J} - 436\text{ J} = \boxed{-246\text{ J}} = Q - W = 0 - W \qquad W_{CD} = \boxed{246\text{ J}}$$

and $\Delta E_{\text{int},DA} = E_{\text{int},A} - E_{\text{int},D} = 125\text{ J} - 190\text{ J} = \boxed{-65.0\text{ J}} = Q - W = Q - 0$

$$Q_{DA} = \boxed{-65.0\text{ J}}$$

For the entire cycle, $\Delta E_{\text{int, net}} = 162\text{ J} + 149 - 246 - 65.0 = \boxed{0}$

$$W_{\text{net}} = -162\text{ J} + 0 + 246\text{ J} + 0 = \boxed{84.3\text{ J}}$$

$$Q_{\text{net}} = 0 + 149\text{ J} + 0 - 65.0\text{ J} = \boxed{84.3\text{ J}}$$

The tables look like:

State	T(K)	P(kPa)	V(cm^3)	E_{int} (J)
A	293	100	500	125
B	673	1840	62.5	287
C	1023	2790	62.5	436
D	445	152	500	190
A	293	100	500	125

Process	Q(J)	W(J)	ΔE_{int}(J)
AB	0	–162	162
BC	149	0	149
CD	0	246	–246
DA	–65.0	0	–65.0

ABCDA	84.3	84.3	0

(c) The input energy is $Q_h = \boxed{149\text{ J}}$, the waste is $Q_c = \boxed{65.0\text{ J}}$, and $W_{\text{net}} = \boxed{84.3\text{ J}}$

(d) The efficiency is: $e = \dfrac{W_{\text{net}}}{Q_h} = \dfrac{84.3\text{ J}}{149\text{ J}} = \boxed{0.565}$

(e) Let f represent the angular speed of the crankshaft. Then $f/2$ is the frequency at which we obtain work in the amount of 84.3 J/cycle:

$$1000\text{ J/s} = (f/2)(84.3\text{ J/cycle})$$

$$f = \frac{2000\text{ J/s}}{84.3\text{ J/cycle}} = 23.7\text{ rev/s} = \boxed{1.42 \times 10^3\text{ rev/min}}$$

***22.23** $(\text{COP})_{\text{refrig}} = \dfrac{T_c}{\Delta T} = \dfrac{270}{30.0} = \boxed{9.00}$

22.24 $(\text{COP})_{\text{heat pump}} = \dfrac{Q_c + W}{W} = \dfrac{T_h}{\Delta T} = \dfrac{295}{25} = \boxed{11.8}$

22.25 (a) For a complete cycle, $\Delta E_{\text{int}} = 0$ and $W = Q_h - Q_c = Q_c\left[\dfrac{Q_h}{Q_c} - 1\right]$

We have already shown that for a Carnot cycle (and only for a Carnot cycle)

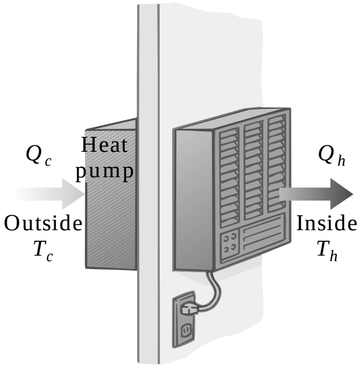
$$\frac{Q_h}{Q_c} = \frac{T_h}{T_c}$$

Therefore, $W = \boxed{Q_c\left[\dfrac{T_h - T_c}{T_c}\right]}$

(b) We have from Equation 22.7, $\text{COP} = \dfrac{Q_c}{W}$.

Using the result from part (a), this becomes

$$\text{COP} = \boxed{\frac{T_c}{T_h - T_c}}$$



***22.26** $\text{COP} = 0.100\ \text{COP}_{\text{Carnot Cycle}}$ or

$$\frac{Q_h}{W} = 0.100\left(\frac{Q_h}{W}\right)_{\text{Carnot Cycle}} = 0.100\left(\frac{1}{\text{Carnot efficiency}}\right)$$

$$= 0.100\left(\frac{T_h}{T_h - T_c}\right) = 0.100\left(\frac{293\text{ K}}{293\text{ K} - 268\text{ K}}\right) = 1.17$$

Thus, $\boxed{\text{1.17 Joules of heat are delivered for each joule of work done.}}$

22.27 $(\text{COP})_{\text{Carnot refrig}} = \dfrac{T_c}{\Delta T} = \dfrac{4.00}{289} \quad \therefore W = \boxed{72.2\text{ J}}$ per 1 J heat removed.

22.28 $(\text{COP})_{\text{Carnot refrig}} = \dfrac{Q_c}{W} = \dfrac{T_c}{T_h - T_c}$ Thus, $W = \boxed{Q\left(\dfrac{T_h - T_c}{T_c}\right)}$

22.29 $\text{COP(refrigerator)} = \dfrac{Q_c}{W}$

(a) If $Q_c = 120$ J and COP = 5.00, then $\boxed{W = 24.0\text{ J}}$

(b) Heat expelled = Heat removed + Work done.

$$Q_h = Q_c + W = 120\text{ J} + 24\text{ J} = \boxed{144\text{ J}}$$

***22.30** A Carnot refrigerator runs on minimum power.

For it: $\dfrac{Q_h}{T_h} = \dfrac{Q_c}{T_c}$ so $\dfrac{Q_h/t}{T_h} = \dfrac{Q_c/t}{T_c}$

Solving part (b) first:

(b) $\dfrac{Q_h}{t} = \dfrac{Q_c}{t}\left(\dfrac{T_h}{T_c}\right) = (8.00\text{ MJ/h})\left(\dfrac{298\text{ K}}{273\text{ K}}\right) = \left(8.73 \times 10^6\ \dfrac{\text{J}}{\text{h}}\right)\left(\dfrac{1\text{ h}}{3600\text{ s}}\right) = \boxed{2.43\text{ kW}}$

(a) $\dfrac{W}{t} = \dfrac{Q_h}{t} - \dfrac{Q_c}{t} = 2.43\text{ kW} - \dfrac{8.00 \times 10^6\text{ J/h}}{3600\text{ s/h}} = \boxed{204\text{ W}}$

22.31 For a freezing process,

$$\Delta S = \frac{\Delta Q}{T} = \frac{-(0.500\text{ kg})(3.33 \times 10^5\text{ J/kg})}{273\text{ K}} = \boxed{-610\text{ J/K}}$$

22.32 At a constant temperature of 4.20 K,

$$\Delta S = \frac{\Delta Q}{T} = \frac{L_v}{4.20\text{ K}} = \frac{20.5\text{ kJ/kg}}{4.20\text{ K}}$$

$$\Delta S = \boxed{4.88\text{ kJ/kg}\cdot\text{K}}$$

22.33 $\Delta S = \displaystyle\int_i^f \frac{dQ}{T} = \int_{T_i}^{T_f} \frac{mcdT}{T} = mc \ln \frac{T_f}{T_i}$

$$\Delta S = (250\text{ g})(1.00\text{ cal/g}\cdot\text{C}°)\ln\left(\frac{353}{293}\right) = 46.6\text{ cal/K} = \boxed{195\text{ J/K}}$$

22.34 From Equation 22.12,

(a) $\Delta S = nC_V \ln(T_f / T_i) + nR \ln(V_f / V_i)$

$$= n\left(\frac{5}{2}\right) R \ln(255\text{ K}/298\text{ K}) + 0$$

$$= -0.390(2.50\text{ mol})(8.315\text{ J/mol}\cdot\text{K}) = \boxed{-8.10\text{ J/K}}$$

(b) The volume now decreases with $V_f / V_i = T_f / T_i$

$$\Delta S = n\left(\frac{5}{2}\right) R \ln(0.856) + nR \ln(0.856)$$

$$= n\left(\frac{7}{2}\right) R \ln(0.856) = nC_P \ln(T_f / T_i)$$

$$= -0.545(2.50\text{ mol})(8.315\text{ J/mol}\cdot\text{K}) = \boxed{-11.3\text{ J/K}}$$

22.35 $\Delta S = \dfrac{Q_2}{T_2} - \dfrac{Q_1}{T_1} = \left(\dfrac{1000}{290} - \dfrac{1000}{5700}\right)\text{ J/K} = \boxed{3.27\text{ J/K}}$

22.36 $c_{\text{iron}} = 448\text{ J/kg °C}\, c_{\text{water}} = 4186\text{ J/kg °C}$

$Q_{\text{cold}} = -Q_{\text{hot}}$

$$(4.00\text{ kg})\left(4186\,\frac{\text{J}}{\text{kg}\cdot\text{C°}}\right)(T_f - 10.0\text{°C}) = -(1.00\text{ kg})\left(448\,\frac{\text{J}}{\text{kg}\cdot\text{C°}}\right)(T_f - 900\text{°C})$$

which yields $T_f = 33.2\text{°C} = 306.2\text{ K}$

$$\therefore \quad \Delta S = \int_{283\text{ K}}^{306.2} \frac{c_{\text{water}} m_{\text{water}}\, dT}{T} + \int_{T = 1173\text{ K}}^{306.2} \frac{c_{\text{iron}} m_{\text{iron}}\, dT}{T}$$

$$\Delta S = c_{\text{water}} m_{\text{water}} \ln\frac{306.2}{283} + c_{\text{iron}} m_{\text{iron}} \ln\frac{306.2}{1173}$$

$$= (4186\text{ J/kg}\cdot\text{K})(4.00\text{ kg})(0.0788) + (448\text{ J/kg}\cdot\text{K})(1.00\text{ kg})(-1.34)$$

$$\Delta S = \boxed{718\text{ J/K}}$$

***22.37** $\Delta S = \dfrac{\frac{1}{2}mv^2}{T} = \dfrac{750(20.0)^2}{293}\text{ J/K} = \boxed{1.02\text{ kJ/K}}$

***22.38** Sitting here writing, I convert chemical energy, in ordered molecules in food, into heat that I put out to the room-temperature surroundings. My heating power is my metabolic rate,

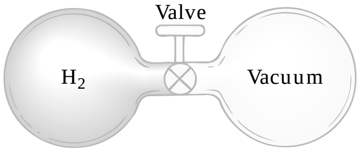
$$2500\text{ kcal/d} = \frac{2500\times 10^3\text{ cal}}{86\,400\text{ s}}\left(\frac{4.186\text{ J}}{1\text{ cal}}\right) = 120\text{ W}$$

My body is in steady state, changing little in entropy, as the environment increases in entropy at the rate

$$\frac{\Delta S}{t} = \frac{Q/T}{t} = \frac{Q/t}{T} = \frac{120\text{ W}}{293\text{ K}} = 0.4\text{ W/K} \sim \boxed{1\text{ W/K}}$$

When using powerful appliances or an automobile, my personal contribution to entropy production is much greater than the above estimate, based only on metabolism.

22.39 $\Delta S = nR\ln\left(\frac{V_f}{V_i}\right) = R\ln 2 = \boxed{5.76\text{ J/K}}$



There is $\boxed{\text{no change in temperature}}$.

***22.40** (a) $V = \frac{nRT_i}{P_i} = \frac{(40.0\text{ g})(8.315\text{ J/mol}\cdot\text{K})(473\text{ K})}{(39.9\text{ g/mol})(100\times 10^3\text{ Pa})} = 39.4\times 10^{-3}\text{ m}^3 = \boxed{39.4\text{ L}}$

(b) $\Delta E_{\text{int}} = nC_V\Delta T = \left(\frac{40.0\text{ gm}}{39.9\text{ g/mol}}\right)\left[\frac{3}{2}\left(8.315\,\frac{\text{J}}{\text{mol}\cdot\text{K}}\right)\right](-200\text{ C°}) = \boxed{-2.50\text{ kJ}}$

(c) $W = 0$ so $Q = \Delta E_{\text{int}} = \boxed{-2.50\text{ kJ}}$

(d) $\Delta S_{\text{argon}} = \int_i^f \frac{dQ}{T} = nC_V\ln\left(\frac{T_f}{T_i}\right)$

$$= \left(\frac{40.0\text{ g}}{39.9\text{ g/mol}}\right)\left[\frac{3}{2}(8.315\text{ J/mol}\cdot\text{K})\right]\ln\left(\frac{273}{473}\right) = \boxed{-6.87\text{ J/K}}$$

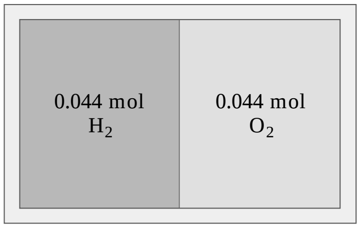
(e) $\Delta S_{\text{bath}} = \frac{2.50\text{ kJ}}{273\text{ K}} = \boxed{+9.16\text{ J/K}}$

The total change in entropy is

$$\Delta S_{\text{total}} = \Delta S_{\text{argon}} + \Delta S_{\text{bath}} = -6.87\text{ J/K} + 9.16\text{ J/K} = +2.29\text{ J/K}$$

$\Delta S_{\text{total}} > 0$ for this irreversible process.

22.41 $\Delta S = nR\ln\left(\frac{V_f}{V_i}\right) = (0.0440)(2)\,R\ln 2 = (0.0880)(8.315)\ln 2 = \boxed{0.507\text{ J/K}}$



22.42 $\Delta S = \int_{T_i = 268\text{ K}}^{T_f = 273\text{ K}} \frac{mc_{\text{ice}}dT}{T} + \frac{mL_{\text{ice}}}{273} = mc_{\text{ice}}\ln\left(\frac{273}{268}\right) + \frac{mL_{\text{ice}}}{273}$

$$\Delta S = (10^5\text{ kg})\left(2010\,\frac{\text{J}}{\text{kg °C}}\right)\ln\left(\frac{273}{268}\right) + \frac{(10^5)(3.33\times10^5)}{273}\text{ J/K} = \boxed{1.26\times10^8\text{ J/K}}$$

22.43 From Equation 22.12, $\Delta S = nC_V\ln\frac{T_f}{T_i} + nR\ln\frac{V_f}{V_i}$

and from the ideal gas law, $\frac{T_f}{T_i} = \frac{P_fV_f}{P_iV_i}$

Thus, $\Delta S = (1.00\text{ mol})\left[\frac{3}{2}\left(8.315\,\frac{\text{J}}{\text{mole}\cdot\text{K}}\right)\right]\ln\left(\frac{(2.00)(0.0400)}{(1.00)(0.0250)}\right)$

$$+ (1.00\text{ mol})\left(8.315\,\frac{\text{J}}{\text{mole}\cdot\text{K}}\right)\ln\left(\frac{0.0400}{0.0250}\right)$$

$\Delta S = \boxed{18.4\text{ J/K}}$

22.44 $\Delta S = nC_V\ln(T_f/T_i) + nR\ln(V_f/V_i)$

$$= (1.00\text{ mol})\left[\frac{5}{2}(8.315\text{ J/mol}\cdot\text{K})\right]\ln\left(\frac{2P\cdot 2V}{PV}\right)$$

$$+ (1.00\text{ mol})\left(8.315\,\frac{\text{J}}{\text{mol}\cdot\text{K}}\right)\ln\left(\frac{2V}{V}\right)$$

$\Delta S = \boxed{34.6\text{ J/K}}$

***22.45** (a) A 12 can only be obtained $\boxed{\text{one}}$ way 6 + 6

(b) A 7 can be obtained $\boxed{\text{six}}$ ways: 6 + 1, 5 + 2, 4 + 3, 3 + 4, 2 + 5, 1 + 6

***22.46** (a) The table is shown below. On the basis of the table, the most probable result of a toss is $\boxed{\text{2 heads and 2 tails}}$.

(b) The most ordered state is the least likely state. Thus, on the basis of the table this is $\boxed{\text{either all heads or all tails}}$.

(c) The most disordered is the most likely state. Thus, this is $\boxed{\text{2 heads and 2 tails}}$.

Result	Possible Combinations	Total
All heads	HHHH	1
3H, 1T	THHH, HTHH, HHTH, HHHT	4
2H, 2T	TTHH, THTH, THHT, HTTH HTHT, HHTT	6
1H, 3T	HTTT, THTT, TTHT, TTTH	4
All tails	TTTT	1

***22.47** (a)

Result	Possible Combinations	Total
All red	RRR	1
2R, 1G	RRG, RGR, GRR	3
1R, 2G	RGG, GRG, GGR	3
All green	GGG	1

(b)

Result	Possible Combinations	Total
All red	RRRRR	1
4R, 1G	RRRRG, RRRGR, RRGRR, RGRRR, GRRRR	5
3R, 2G	RRRGG, RRGRG, RGRRG, GRRRG, RRGGR, RGRGR, GRRGR, RGGRR, GRGRR, GGRRR	10
2R, 3G	GGGRR, GGRGR, GRGGR, RGGGR, GGRRG, GRGRG, RGGRG, GRRGG, RGRGG, RRGGG	10
1R, 4G	RGGGG, GRGGG, GGRGG, GGGRG, GGGGR	5
All green	GGGGG	1

***22.48** The conversion of gravitational potential energy into kinetic energy as the water falls is reversible. But the subsequent conversion into internal energy is not. We imagine arriving at the same final state by adding heat, in amount *mgy*, to the water from a stove at a temperature infinitesimally above 20.0°C. Then,

$$\Delta S = \int \frac{dQ}{T} = \frac{Q}{T} = \frac{mgy}{T}$$

$$= \frac{(5000\ \text{m}^3)(1000\ \text{kg/m}^3)(9.80\ \text{m/s}^2)(50.0\ \text{m})}{293\ \text{K}} = \boxed{8.36 \times 10^6\ \text{J/K}}$$

22.49 $e = \dfrac{W}{Q_h} = 0.350 \qquad W = 0.350Q_h$

$Q_h = W + Q_c \qquad Q_c = 0.650Q_h$

$$\text{COP(refrigerator)} = \frac{Q_c}{W} = \frac{0.650Q_h}{0.350Q_h} = \boxed{1.86}$$

22.50 $Q_c = mc\,\Delta T + mL + mc\,\Delta T$

$$= 0.500\text{ kg}(4186\text{ J/kg}\cdot\text{C°})10.0\text{ C°} + 0.500\text{ kg}(3.33\times10^5\text{ J/kg})$$

$$+\,0.500\text{ kg}(2090\text{ J/kg}\cdot\text{C°})20.0\text{ C°} = 2.08\times10^5\text{ J}$$

$$\frac{Q_c}{W} = \text{COP}_c\text{ (refrigerator)} = \frac{T_c}{T_h - T_c}$$

$$W = \frac{Q_c\,(T_h - T_c)}{T_c} = \frac{(2.08\times10^5\text{ J})\,[20.0\text{°C} - (-20.0\text{°C})]}{(273 - 20.0)\text{K}} = \boxed{32.9\text{ kJ}}$$

22.51 $\dfrac{dQ}{dt} = 5000\text{ W}$ $T_h = 295\text{ K}$ $T_c = 268\text{ K}$

(a) If $\dfrac{\Delta Q}{\Delta t} = \dfrac{\Delta E}{\Delta t}$ then $\boxed{\wp_{\text{El}} = 5.00\text{ kW}}$

(b) For a heat pump,

$$(\text{COP})_{\text{Carnot}} = \frac{T_h}{\Delta T} = \frac{295}{27.0} = 10.9$$

Actual COP = (0.600)(10.9) = 6.55

Therefore, to bring 5000 W of heat into the house only requires $\boxed{763\text{ W}}$

Goal Solution

G: The electric heater should be 100% efficient, so $P = 5$ kW. The heat pump is only 60% efficient, so we might expect $P = 9$ kW.

O: Power is the change of energy per unit of time, so we can find the power for both cases by examining the change in heat energy.

A: (a) $P_{\text{electric}} = \dfrac{\Delta E}{\Delta t}$ so if all of the electricity is converted into internal energy, $\Delta E = \Delta Q$.

Therefore, $P_{\text{electric}} = \dfrac{\Delta Q}{\Delta t} = 5000\text{ W}$

(b) For a heat pump, $(\text{COP})_{\text{Carnot}} = \dfrac{T_h}{\Delta T} = \dfrac{295\text{ K}}{27\text{ K}} = 10.92$

Actual COP = (0.6)(10.92) = 6.55 $= \dfrac{Q_h}{W} = \dfrac{Q_h/t}{W/t}$

Therefore, to bring 5000 W of heat into the house only requires input power

$$P_{\text{heat pump}} = \frac{W}{t} = \frac{Q_h/t}{\text{COP}} = \frac{5000\text{ W}}{6.56} = 763\text{ W}$$

L: The result for the electric heater's power is consistent with our prediction, but the heat pump actually requires *less* power than we expected. Since both types of heaters use electricity to operate, we can now see why it is more cost effective to use a heat pump even though it is less than 100% efficient!

***22.52** $\Delta S_{\text{hot}} = \dfrac{-1000}{600}\dfrac{\text{J}}{\text{K}}$

$\Delta S_{\text{cold}} = \dfrac{+750}{350}\dfrac{\text{J}}{\text{K}}$

(a) $\Delta S_U = \Delta S_{\text{hot}} + \Delta S_{\text{cold}} = \boxed{0.476 \text{ J/K}}$

(b) $e_C = 1 - \dfrac{T_1}{T_2} = 0.417$

$W = Q_h e_C = (1000 \text{ J})(0.417) = \boxed{417 \text{ J}}$

(c) $W_{\text{net}} = 417 \text{ J} - 250 \text{ J} = 167 \text{ J}$

$T_1 \Delta S_U = (350 \text{ K})(0.476 \text{ J/K}) = \boxed{167 \text{ J}}$

22.53 (a) For an isothermal process, $Q = nRT \ln\left(\dfrac{V_2}{V_1}\right)$

Therefore, $Q_1 = nR(3T_i)\ln 2$ and $Q_3 = nR(T_i)\ln(1/2)$

For the constant volume processes, we have

$Q_2 = \Delta E_{\text{int},2} = \dfrac{3}{2}nR(T_i - 3T_i)$ and $Q_4 = \Delta E_{\text{int},4} = \dfrac{3}{2}nR(3T_i - T_i)$

The net heat transferred is then

$Q = Q_1 + Q_2 + Q_3 + Q_4$ or $Q = \boxed{2nRT_i \ln 2}$

(b) Heat > 0 is the heat added to the system. Therefore,

$Q_h = Q_1 + Q_4 = 3nRT_i(1 + \ln 2)$

Since the change in temperature for the complete cycle is zero,

$\Delta E_{\text{int}} = 0$ and $W = Q$

Therefore, the efficiency is

$$e_C = \frac{W}{Q_h} = \frac{Q}{Q_h} = \frac{2 \ln 2}{3(1 + \ln 2)} = \boxed{0.273}$$

***22.54** $\text{COP} = 3.00 = \frac{Q_c}{W}$ Therefore, $W = \frac{Q_c}{3.00}$

The heat removed each minute is

$$\frac{Q_C}{t} = (0.0300\text{ kg})(4186\text{ J/kg°C})(22.0\text{°C}) + (0.0300\text{ kg})(3.33 \times 10^5\text{ J/kg})$$

$$+ (0.0300\text{ kg})(2090\text{ J/kg°C})(20.0\text{°C}) = 1.40 \times 10^4\text{ J/min}$$

or, $\frac{Q_c}{t} = 233\text{ J/s}$

Thus, the work done per sec $= \wp = \frac{233\text{ J/s}}{3.00} = \boxed{77.8\text{ W}}$

22.55 $\frac{Q_c}{W} = \text{COP}_\text{C}\text{ (refrigerator)} = \frac{T_c}{T_h - T_c} = \frac{Q_c/t}{W/t}$

$$\frac{0.150\text{ W}}{W/t} = \frac{260\text{ K}}{40.0\text{ K}}$$

$$\wp = \frac{W}{t} = (0.150\text{ W})\frac{40.0\text{ K}}{260\text{ K}} = \boxed{23.1\text{ mW}}$$

22.56 (a) $\frac{W}{t} = 1.50 \times 10^8\text{ W}_{\text{(electrical)}}$, $Q = mL = \left[\frac{W/t}{0.150}\right]\Delta t$,

and $L = 33.0\text{ kJ/g} = 33.0 \times 10^6\text{ J/kg}$

$$m = \left[\frac{W/t}{0.150}\right]\Delta t/L$$

$$m = \frac{(1.50 \times 10^8\text{ W})(86{,}400\text{ s/day})}{0.150(33.0 \times 10^6\text{ J/kg})(10^3\text{ kg/metric ton})} = \boxed{2620\text{ metric tons/day}}$$

(b) Cost = ($8.00 / metric ton)(2618 metric tons / day)(365 days / y)

Cost = $\boxed{\$7.65\text{ million/year}}$

(c) First find the rate at which heat energy is discharged into the water. If the plant is 15.0% efficient in producing electrical energy then the rate of heat production is

$$\frac{Q_c}{t} = \left(\frac{W}{t}\right)\left(\frac{1}{e} - 1\right) = (1.50 \times 10^8\text{ W})\left(\frac{1}{0.150} - 1\right) = 8.50 \times 10^8\text{ W}$$

Then, $\frac{Q_c}{t} = \frac{mc\Delta T}{t}$ and

$$\frac{m}{t} = \frac{Q_c / t}{c\,\Delta T} = \frac{8.50 \times 10^8 \text{ J/s}}{(4186 \text{ J/kg} \cdot \text{C°})(5.00 \text{ C°})} = \boxed{4.06 \times 10^4 \text{ kg/s}}$$

***22.57** $e_C = 1 - \frac{T_c}{T_h} = \frac{W}{Q_h} = \frac{(W/t)}{(Q_h/t)}$

$$\frac{Q_h}{t} = \frac{\wp}{\left(1 - \frac{T_c}{T_h}\right)} = \frac{\wp T_h}{(T_h - T_c)}$$

$$Q_h = W + Q_c$$

$$\frac{Q_c}{t} = \frac{Q_h}{t} - \frac{W}{t}$$

$$\frac{Q_c}{t} = \frac{\wp T_h}{(T_h - T_c)} - \wp = \frac{\wp T_c}{(T_h - T_c)}$$

$$Q_c = mc\,\Delta T$$

$$\frac{Q_c}{t} = \left(\frac{m}{t}\right) c\,\Delta T = \frac{\wp T_c}{(T_h - T_c)}$$

$$\frac{m}{t} = \frac{\wp T_c}{(T_h - T_c)\,c\,\Delta T}$$

$$\frac{m}{t} = \frac{(1.00 \times 10^9\text{ W})(300\text{ K})}{(200\text{ K})(4186\text{ J/kg}\cdot\text{C°})(6.00\text{ C°})} = \boxed{5.97 \times 10^4\text{ kg/s}}$$

22.58 $e_C = 1 - \frac{T_c}{T_h} = \frac{W}{Q_h} = \frac{\left(\frac{W}{t}\right)}{\left(\frac{Q_h}{t}\right)}$

$$\left(\frac{Q_h}{t}\right) = \frac{\wp}{\left(1 - \frac{T_c}{T_h}\right)} = \frac{\wp T_h}{(T_h - T_c)}$$

$$\left(\frac{Q_c}{t}\right) = \left(\frac{Q_h}{t}\right) - \wp = \frac{\wp T_c}{(T_h - T_c)}$$

$Q_c = mc\,\Delta T$, where c = the specific heat of water.

$$\therefore \left(\frac{Q_c}{t}\right) = \left(\frac{m}{t}\right) c\,\Delta T = \frac{\wp T_c}{(T_h - T_c)}$$

$$\therefore \frac{m}{t} = \boxed{\frac{\wp T_c}{(T_h - T_c)\,c\,\Delta T}}$$

***22.59** (a) $35.0°\text{F} = \frac{5}{9}(35.0 - 32.0)\ °\text{C} = (1.67 + 273.15)\text{K} = 274.82\text{ K}$

$98.6°\text{F} = \frac{5}{9}(98.6 - 32.0)\ °\text{C} = (37.0 + 273.15)\text{K} = 310.15\text{ K}$

$$\Delta S_{\text{ice water}} = \int \frac{dQ}{T} = (453.6\text{ g})(1.00\text{ cal/g}\cdot\text{K}) \times \int_{274.82}^{310.15} \frac{dT}{T}$$

$$= 453.6 \ln\left(\frac{310.15}{274.82}\right) = 54.86\text{ cal/K}$$

$$\Delta S_{\text{body}} = -\frac{|Q|}{T_{\text{body}}} = -(453.6)(1.00)\frac{(310.15 - 274.82)}{310.15} = -51.67\text{ cal/K}$$

$$\Delta S_{\text{system}} = 54.86 - 51.67 = \boxed{3.19\text{ cal/K}}$$

(b) $(453.6)(1)(T_F - 274.82) = (70.0 \times 10^3)(1)(310.15 - T_F)$

Thus,

$$(70.0 + 0.4536) \times 10^3\ T_F = [(70.0)(310.15) + (0.4536)(274.82)] \times 10^3$$

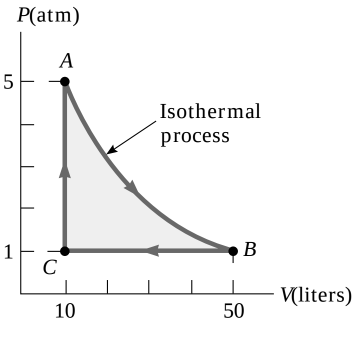
and $T_F = 309.92\text{ K} = 36.77°\text{C} = \boxed{98.19°\text{F}}$

$$\Delta S'_{\text{ice water}} = 453.6 \ln\left(\frac{309.92}{274.82}\right) = 54.52\text{ cal/K}$$

$$\Delta S'_{\text{body}} = -(70.0 \times 10^3) \ln\left(\frac{310.15}{309.92}\right) = -51.93\text{ cal/K}$$

$\Delta S'_{\text{sys}} = 54.52 - 51.93 = \boxed{2.59\text{ cal/K}}$ which is less than the estimate in part (a).

22.60 (a) For the isothermal process AB,



$$W_{AB} = P_A V_A \ln\left(\frac{V_B}{V_A}\right)$$

$$W_{AB} = (5)(1.013 \times 10^5\text{ Pa})(10.0 \times 10^{-3}\text{ m}^3) \ln\left(\frac{50.0}{10.0}\right)$$

$$W_{AB} = 8.15 \times 10^3\text{ J}$$

where we have used $1.00\text{ atm} = 1.013 \times 10^5\text{ Pa}$

and $1.00\text{ L} = 1.00 \times 10^{-3}\text{ m}^3$.

$$W_{BC} = P_B\,\Delta V = (1.013 \times 10^3\text{ Pa})[(10.0 - 50.0) \times 10^{-3}]\text{m}^3 = -4.05 \times 10^3\text{ J}$$

$$W_{CA} = 0 \quad \text{and} \quad W = W_{AB} + W_{BC} = 4.11 \times 10^3\text{ J} = \boxed{4.11\text{ kJ}}$$

(b) Since AB is an isothermal process, $\Delta E_{\text{int},AB} = 0$, and

$$Q_{AB} = W_{AB} = 8.15 \times 10^3\text{ J}$$

For an ideal monatomic gas, $C_V = 3R/2$ and $C_P = 5R/2$.

$$T_B = T_A = P_B V_B / nR = (1.013 \times 10^5)(50.0 \times 10^{-3}) / R = 5.05 \times 10^3 / R$$

Also, $T_C = P_C V_C / nR = (1.013 \times 10^5)(10.0 \times 10^{-3}) / R = 1.01 \times 10^3 / R$

$$Q_{\text{CA}} = nC_V\,\Delta T = (1.00)\left(\frac{3}{2}R\right)\left(\frac{5.05 \times 10^3 - 1.01 \times 10^3}{R}\right) = 6.08\text{ kJ}$$

so the total heat absorbed is $Q_{AB} + Q_{CA} = 8.15\text{ kJ} + 6.08\text{ kJ} = \boxed{14.2\text{ kJ}}$

(c) $Q_{BC} = nC_P\,\Delta T = \frac{5}{2}(nR\,\Delta T) = \frac{5}{2}\,P_B\,\Delta V_{BC}$

$$Q_{BC} = \frac{5}{2}(1.013 \times 10^5)\,[(10.0 - 50.0) \times 10^{-3}] = -1.01 \times 10^4\text{ J} = \boxed{-10.1\text{ kJ}}$$

(d) $e = \frac{W}{Q_h} = \frac{W}{Q_{AB} + Q_{CA}} = \frac{4.11 \times 10^3\text{ J}}{1.42 \times 10^4\text{ J}} = 0.289$ or $\boxed{28.9\%}$

22.61 Define T_1 = Temp Cream = 5.00°C = 278 K

Define T_2 = Temp Coffee = 60.0°C = 333 K

The final temperature of the mixture is:

$$T_f = \frac{(20.0\text{ g})T_1 + (200\text{ g})T_2}{220\text{ g}} = 55.0°\text{C} = 328\text{ K}$$

The entropy change due to this mixing is

$$\Delta S = (20.0\text{ g})\int_{T_1}^{T_f}\frac{c_V dT}{T} + (200\text{ g})\int_{T_2}^{T_f}\frac{c_V dT}{T}$$

$$\Delta S = (84.0\text{ J/K})\ln\left(\frac{T_f}{T_1}\right) + (840\text{ J/K})\ln\left(\frac{T_f}{T_2}\right)$$

$$= (84.0\text{ J/K})\ln\left(\frac{328}{278}\right) + (840\text{ J/K})\ln\left(\frac{328}{333}\right)$$

$$\Delta S = \boxed{+1.18\text{ J/K}}$$

***22.62** (a) $10.0\,\frac{\text{Btu}}{\text{h}\cdot\text{W}}\left(\frac{1055\text{ J}}{1\text{ Btu}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right)\left(\frac{1\text{ W}}{1\text{ J/s}}\right) = \boxed{2.93}$

(b) Coefficient of performance for a refrigerator: $\boxed{(\text{COP})_{\text{refrigerator}}}$

(c) With EER $5 = \frac{10{,}000\text{ Btu/h}}{\wp}$ $\qquad \wp = \frac{10{,}000\text{ W}}{5} = 2000\text{ W} = 2.00\text{ kW}$

Energy purchased $= \wp t = (2.00\text{ kW})(1500\text{ h}) = 3.00\times10^3\text{ kWh}$

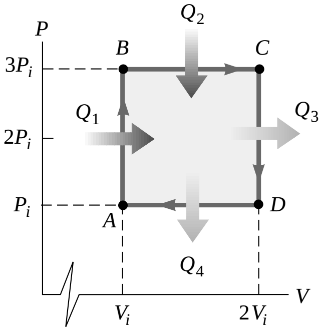
$$\text{Cost} = (3.00\times10^3\text{ kWh})\left(0.100\,\frac{\$}{\text{kWh}}\right) = \$300$$

With EER $10 = \frac{10{,}000\text{ Btu/h}}{\wp}$ $\qquad \wp = \frac{10{,}000\text{ W}}{10} = 1000\text{ W} = 1.00\text{ kW}$

Energy purchased $= \wp t = (1.00\text{ kW})(1500\text{ h}) = 1.50\times10^3\text{ kWh}$

$$\text{Cost} = (1.50\times10^3\text{ kWh})\left(0.100\,\frac{\$}{\text{kWh}}\right) = \$150$$

Thus, the cost for air conditioning is $\boxed{\text{half as much with EER 10}}$



22.63 At point A, $P_iV_i = nRT_i$ and $n = 1.00$ mol

At point B, $3P_iV_i = nRT_B$ so $T_B = 3T_i$

At point C, $(3P_i)(2V_i) = nRT_C$, and $T_C = 6T_i$

At point D, $P_i(2V_i) = nRT_D$, so $T_D = 2T_i$

The heat transfer for each step in the cycle is found using $C_V = 3R/2$ and $C_P = 5R/2$.

$$Q_{AB} = nC_V(3T_i - T_i) = 3nRT_i$$

$$Q_{BC} = nC_P(6T_i - 3T_i) = 7.50nRT_i \quad \text{and} \quad Q_{CD} = nC_V(2T_i - 6T_i) = -6nRT_i$$

$Q_{DA} = nC_P\,(T_i - 2T_i) = -2.50nRT_i$. Therefore,

(a) $Q_{(\text{entering})} = Q_h = Q_{AB} + Q_{BC} = \boxed{10.5nRT_i}$

(b) $Q_{(\text{leaving})} = Q_c = \left|Q_{CD} + Q_{DA}\right| = \boxed{8.50nRT_i}$

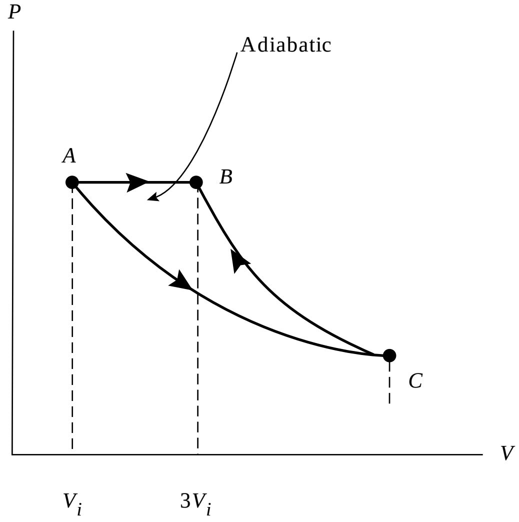
(c) Actual efficiency, $e = \dfrac{Q_h - Q_c}{Q_h} = \boxed{0.190}$

(d) Carnot efficiency, $e_C = 1 - \dfrac{T_c}{T_h} = 1 - \dfrac{T_i}{6T_i} = \boxed{0.833}$

22.64 (a) $W = \int_{V_i}^{V_f} P\,dV = nRT\int_{V_i}^{2V_i} \dfrac{dV}{V} = (1.00)RT\ln\left(\dfrac{2V_i}{V_i}\right) = \boxed{RT\ln 2}$

(b) $\boxed{\text{The second law refers to cycles.}}$

22.65 The isobaric process AB is shown along with an isotherm AC and an adiabat CB in the PV diagram. Since the change in entropy is path independent, $\Delta S_{AB} = \Delta S_{AC} + \Delta S_{CB}$ and $\Delta S_{CB} = 0$ for an adiabatic process. Since $T_C = T_A$, Equation 22.12 gives



$$\Delta S_{AC} = nR\ln\left(\frac{V_C}{V_A}\right)$$

For isotherm AC, $P_AV_A = P_CV_C$ and for adiabat CB, $P_CV_C^\gamma = P_BV_B^\gamma$

Combining gives: $V_C = \left[\dfrac{P_BV_B^\gamma}{P_AV_A}\right]^{1/(\gamma-1)}$

$$= \left[\left(\frac{P_A}{P_A}\right)\frac{(3V_i)^\gamma}{V_i}\right]^{1/(\gamma-1)} = 3^{\gamma/(\gamma-1)}V_i$$

Thus, $\Delta S_{AB} = 0 + \Delta S_{AC} = nR\ln[3^{\gamma/(\gamma-1)}] = nR\left(\dfrac{\gamma}{\gamma-1}\right)\ln 3$

But, $\dfrac{\gamma}{\gamma-1} = \dfrac{C_P/C_V}{C_P/C_V - 1} = \dfrac{C_P}{C_P - C_V} = \dfrac{C_P}{R}$

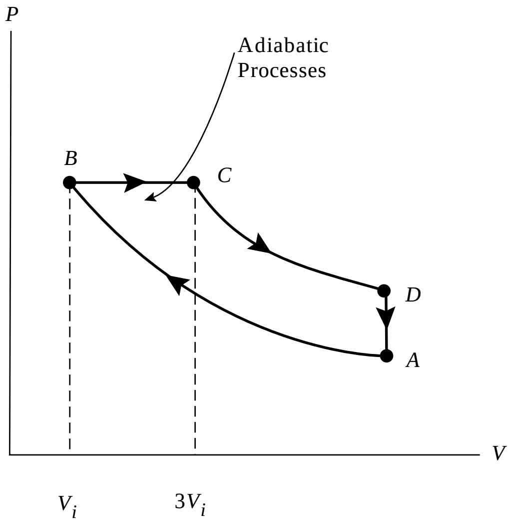
$\therefore \Delta S = \boxed{nC_P \ln 3}$

22.66 Simply evaluate the maximum (Carnot) efficiency.

$$e_C = \frac{\Delta T}{T_h} = \frac{4.00\text{ K}}{277\text{ K}} = \boxed{0.0144}$$

The proposal does not merit serious consideration.

22.67 The heat transfer over the paths CD and BA is zero since they are adiabats.



Over path BC: $Q_{BC} = nC_P(T_C - T_B) > 0$

Over path DA: $Q_{DA} = mC_V(T_A - T_D) < 0$

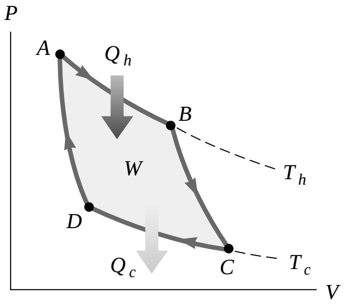
Therefore, $Q_c = \left|Q_{DA}\right|$ and $Q_h = Q_{BC}$

The efficiency is then

$$e = 1 - \frac{Q_c}{Q_h} = 1 - \frac{(T_D - T_A)}{(T_C - T_B)}\frac{C_V}{C_P}$$

$$e = 1 - \frac{1}{\gamma}\left[\frac{(T_D - T_A)}{T_C - T_B}\right]$$

22.68 (a) Use the equation of state for an ideal gas



$$V = nRT/P$$

$$V_A = \frac{(1.00)(8.315)(600)}{(25.0)(1.013\times 10^5)} = \boxed{1.97\times 10^{-3}\text{ m}^3}$$

$$V_C = \frac{(1.00)(8.315)(400\text{ K})}{1.013\times 10^5} = \boxed{32.8\times 10^{-3}\text{ m}^3}$$

Since AB is isothermal, $P_AV_A = P_BV_B$, and since BC is adiabatic, $P_BV_B^{\gamma} = P_CV_C^{\gamma}$.

Combining these expressions, $V_B = \left[\left(\frac{P_C}{P_A}\right)\frac{V_C^{\gamma}}{V_A}\right]^{1/(\gamma-1)}$

$$V_B = [(1.00/25.0)(32.8\times 10^{-3}\text{ m}^3)^{1.40}/(1.97\times 10^{-3}\text{ m}^3)]^{(1/0.400)} = \boxed{11.9\times 10^{-3}\text{ m}^3}$$

Similarly, $V_D = [(P_A/P_C)(V_A^{\gamma}/V_C)]^{1/(\gamma-1)}$, or

$$V_D = [(25.0/1.00)(1.97\times 10^{-3}\text{ m}^3)^{1.40}/(32.8\times 10^{-3}\text{ m}^3)]^{(1/0.400)} = \boxed{5.44\times 10^{-3}\text{ m}^3}$$

Since AB is isothermal, $P_A V_A = P_B V_B$ and

$$P_B = P_A\left(\frac{V_A}{V_B}\right) = (25.0\text{ atm})\left(\frac{1.97\times10^{-3}\text{ m}^3}{11.9\times10^{-3}\text{ m}^3}\right) = \boxed{4.14\text{ atm}}$$

Also, CD is isothermal and

$$P_D = P_C\left(\frac{V_C}{V_D}\right) = (1.00\text{ atm})\left(\frac{32.8\times10^{-3}\text{ m}^3}{5.44\times10^{-3}\text{ m}^3}\right) = \boxed{6.03\text{ atm}}$$

Solving part (c) before part (b):

(c) For this Carnot cycle, $e_C = 1 - \frac{T_c}{T_h} = 1 - \frac{400\text{ K}}{600\text{ K}} = \boxed{0.333}$

(b) Heat energy is added to the gas during the process AB. For this isothermal process, $\Delta E_{\text{int}} = 0$, and the first law gives

$$Q_{AB} = W_{AB} = nRT_h \ln\left(\frac{V_B}{V_A}\right) \quad \text{or}$$

$$Q_h = Q_{AB} = (1.00\text{ mol})\left(8.315\,\frac{\text{J}}{\text{mol}\cdot\text{K}}\right)(600\text{ K})\ \ln\left(\frac{11.9}{1.97}\right) = 8.97\text{ kJ}$$

Then, from $e = W_{\text{net}}/Q_h$, the net work done per cycle is

$$W_{\text{net}} = e_C Q_h = 0.333(8.97\text{ kJ}) = \boxed{2.99\text{ kJ}}$$

22.69 (a) $\frac{dQ}{dt} = (2.00\times10^6\text{ cal}\times4.186\text{ J/cal})/(24.0\text{ h}\times3600\text{ s/h})$

$$= \boxed{96.9\text{ W}} = \boxed{8.33\times10^4\text{ cal/h}}$$

(b) $\frac{dT}{dt} = \frac{dQ/dt}{mc} = \frac{8.33\times10^4\text{ cal/h}}{(70.0\times10^3\text{ g})(1.00\text{ cal/g}\cdot{}^\circ\text{C})}$

$$= \boxed{1.19^\circ\text{C/h}} = \boxed{2.14^\circ\text{F/h}}$$

22.70 (a) $\boxed{20.0°\text{C}}$

(b) $\Delta S = mc\ln\dfrac{T_f}{T_1} + mc\ln\dfrac{T_f}{T_2}$

$$= (1.00\text{ kg})(4.19\text{ kJ/kg}\cdot\text{K})\left[\ln\frac{T_f}{T_1} + \ln\frac{T_f}{T_2}\right]$$

$$\Delta S = (4.19\text{ kJ/K})\ln\left(\frac{293}{283}\cdot\frac{293}{303}\right)$$

(c) $\Delta S = \boxed{+4.88\text{ J/K}}$

(d) $\boxed{\text{Yes}}$ Entropy has increased.