# Chapter 17

# Energy in Thermal Processes: The First Law of Thermodynamics

**CHAPTER OUTLINE**

## ANSWERS TO QUESTIONS

**Q17.1** Temperature is a measure of molecular motion. Heat is energy in the process of being transferred between objects by random molecular collisions. Internal energy is an object's energy of random molecular motion and molecular interaction.

**Q17.2** The $\Delta T$ is twice as great in the ethyl alcohol.

**Q17.3** The final equilibrium temperature will show no significant increase over the initial temperature of the water.

**Q17.4** Some water may boil away. You would have to very precisely measure how much, and very quickly measure the temperature of the steam; it is not necessarily 100°C.

**Q17.5** Heat is energy being transferred, not energy contained in an object. Further, a large-mass object, or an object made of a material with high specific heat, can contain more internal energy than a higher-temperature object.

**Q17.6** There are three properties to consider here: thermal conductivity, specific heat, and mass. With dry aluminum, the thermal conductivity of aluminum is much greater than that of (dry) skin. This means that the internal energy in the aluminum can more readily be transferred to the atmosphere than to your fingers. In essence, your skin acts as a thermal insulator to some degree (pun intended). If the aluminum is wet, it can wet the outer layer of your skin to make it into a good conductor of heat; then more internal energy from the aluminum can get into you. Further, the water itself, with additional mass and with a relatively large specific heat compared to aluminum, can be a significant source of extra energy to burn you. In practical terms, when you let go of a hot, dry piece of aluminum foil, the heat transfer immediately ends. When you let go of a hot *and* wet piece of aluminum foil, the hot water sticks to your skin, continuing the heat transfer, and resulting in more energy transfer to you!

**Q17.7** Write $1\,000\text{ kg}(4\,186\text{ J/kg °C})(1\text{°C}) = V(1.3\text{ kg/m}^3)(1\,000\text{ J/kg °C})(1\text{°C})$ to find $V = 3.2\times10^3\text{ m}^3$

**Q17.8** (a) and (b) both increase by minuscule amounts.

**Q17.9** If the system is isolated, no energy enters or leaves the system by heat, work, or other transfer processes. Within the system energy can change from one form to another, but since energy is conserved these transformations cannot affect the total amount of energy. The total energy is constant.

**Q17.10** Yes. If you know the different specific heats of zinc and copper, you can determine the fraction of each by heating a known mass of pennies to a specific initial temperature, say 100°C, and dumping them into a known quantity of water, at say 20°C. The final temperature $T$ will reveal the metal content:

$$m_{\text{pennies}}\left[xc_{\text{Cu}} + (1-x)c_{\text{Zn}}\right](100\text{°C} - T) = m_{\text{H}_2\text{O}}c_{\text{H}_2\text{O}}(T - 20\text{°C}).$$

Since all quantities are known, except $x$, the fraction of the penny that is copper will be found by putting in the experimental numbers $m_{\text{pennies}}$, $m_{\text{H}_2\text{O}}$, $T(\text{final})$, $c_{\text{Zn}}$, and $c_{\text{Cu}}$.

**Q17.11** The tile is a better thermal conductor than carpet. Thus, energy is conducted away from your feet more rapidly by the tile than by the carpeted floor.

**Q17.12** The question refers to baking in a conventional oven, not to microwaving. The metal has much higher thermal conductivity than the potato. The metal quickly conducts energy from the hot oven into the center of potato.

**Q17.13** In winter the interior of the house is warmer than the air outside. On a summer day we want the interior to stay cooler than the exterior. Heavy draperies over the windows can slow down energy transfer by conduction, by convection, and by radiation, to make it easier to maintain the desired difference in temperature.

**Q17.14** In winter the produce is protected from freezing. The heat capacity of the earth is so high that soil freezes only to a depth of a few decimeters in temperate regions. Throughout the year the temperature will stay nearly constant all day and night. Factors to be considered are the insulating properties of soil, the absence of a path for energy to be radiated away from or to the vegetables, and the hindrance to the formation of convection currents in the small, enclosed space.

**Q17.15** The high mass and specific heat of the barrel of water and its high heat of fusion mean that a large amount of energy would have to leak out of the cellar before the water and the produce froze solid. Evaporation of the water keeps the relative humidity high to protect foodstuffs from drying out.

**Q17.16** The porcelain of the teacup is a thermal insulator. That is, it is a thermal conductor of relatively low conductivity. When you wrap your hands around a cup of hot tea, you make $A$ large and $L$ small in the equation $\mathcal{P} = kA\dfrac{T_h - T_c}{L}$ for the rate of energy transfer by heat from tea into you. When you hold the cup by the handle, you make the rate of energy transfer much smaller by reducing $A$ and increasing $L$. The air around the cup handle will also reduce the temperature where you are touching it. A paper cup can be fitted into a tubular jacket of corrugated cardboard, with the channels running vertically, for remarkably effective insulation, according to the same principles.

**Q17.17** Keep them dry The air pockets in the pad conduct energy by heat, but only slowly. Wet pads would absorb some energy in warming up themselves, but the pot would still be hot and the water would quickly conduct and convect a lot of energy right into you.

**Q17.18** The person should add the cream immediately when the coffee is poured, rather than later when he is ready to drink it Then the smaller temperature difference between coffee and environment will reduce the rate of energy loss during the several minutes Also, the lighter color of the coffee with cream may reduce the emissivity to decrease the radiated power

**Q17.19** Convection The bridge deck loses energy rapidly to the air both above it and below it

**Q17.20** The marshmallow has very small mass compared to the saliva in the teacher's mouth and the surrounding tissues. Mostly air and sugar, the marshmallow also has a low specific heat compared to living matter. Then the marshmallow can zoom up through a large temperature change while causing only a small temperature drop of the teacher's mouth. The marshmallow is a foam with closed cells and it carries very little liquid nitrogen into the mouth. The liquid nitrogen still on the marshmallow comes in contact with the much hotter saliva and immediately boils into cold gaseous nitrogen. This nitrogen gas has very low thermal conductivity. It creates an insulating thermal barrier between the marshmallow and the teacher's mouth (the Leydenfrost effect) A similar effect can be seen when water droplets are put on a hot skillet Each one dances around as it slowly shrinks, because it is levitated on a thin film of steam. The most extreme demonstration of this effect is pouring liquid nitrogen into one's mouth and blowing out a plume of nitrogen gas. We strongly recommend that you read of Jearl Walker's adventures with this demonstration rather than trying it.

**Q17.21** (a) Warm a pot of coffee on a hot stove.

(b) Consider an ice cube at 0°C in a glass of lemonade on a picnic table. The ice will absorb energy while melting, but not increase in temperature.

(c) Let a high-pressure gas at room temperature slowly expand by pushing on a piston. Work comes out of the gas in a constant-temperature expansion as the same quantity of heat flows in from the surroundings.

(d) Warm your hands by rubbing them together. Heat your tepid coffee in a microwave oven. Energy input by work, by electromagnetic radiation, or by other means, can all alike produce a temperature increase.

(e) Davy's experiment is an example of this process.

(f) This is not necessarily true Consider some supercooled liquid water, unstable but with temperature below 0°C. Drop in a snowflake or a grain of dust to trigger its freezing into ice, and the release of internal energy measured by its latent heat of fusion can actually push its temperature up

**Q17.22** Partially evacuating the container is equivalent to letting the remaining gas expand. This means that the gas does work, making its internal energy and hence its temperature decrease. The liquid in the container will eventually reach thermal equilibrium with the low pressure gas This effect of an expanding gas decreasing in temperature is a key process in your refrigerator or air conditioner.

## SOLUTIONS TO PROBLEMS

### Section 17.1 Heat and Internal Energy

**P17.1** Imagine a mass $m$ of water contained in a styrofoam box, which prevents any energy flow into or out of it by heat. As the water falls the gravitational energy of the water-Earth system turns into kinetic energy of organized (downward) motion of the water, then into kinetic energy of disorganized (splashing around) macroscopic motion, and at last into kinetic energy of random molecular motion, which is internal energy. There is 100% conversion efficiency from gravitational into internal energy. Heat is not involved in the warming process, but imagine a process in which the mass $m$ of water is placed on a stove and energy $mgy$ is put into it by heat. The temperature change is then specified by

$$mgy = mc\Delta T$$

$$\Delta T = \frac{gy}{c} = \frac{\left(9.80\ \text{m/s}^2\right)(120\ \text{m})}{4186\ \text{J/kg}\cdot{}^\circ\text{C}}\left(\frac{1\ \text{J}}{1\ \text{kg}\cdot\text{m}^2/\text{s}^2}\right) = \boxed{0.281^\circ\text{C}}$$

**P17.2** The container is thermally insulated, so no energy flows by heat:

$$Q = 0$$

and $\quad \Delta E_{\text{int}} = Q + W_{\text{input}} = 0 + W_{\text{input}} = 2mgh$

The work on the falling weights is equal to the work done on the water in the container by the rotating blades. This work results in an increase in internal energy of the water:

$$2mgh = \Delta E_{\text{int}} = m_{\text{water}} c\Delta T$$

$$\Delta T = \frac{2mgh}{m_{\text{water}} c} = \frac{2\times 1.50\ \text{kg}\left(9.80\ \text{m/s}^2\right)(3.00\ \text{m})}{0.200\ \text{kg}(4186\ \text{J/kg}\ {}^\circ\text{C})} = \frac{88.2\ \text{J}}{837\ \text{J/}^\circ\text{C}} = \boxed{0.105^\circ\text{C}}$$

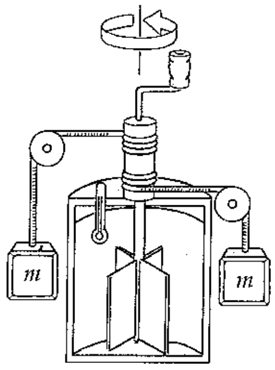

FIG. P17.2

### Section 17.2 Specific Heat

**P17.3** From $\quad Q = mc\Delta T$

we find $\quad \Delta T = \dfrac{Q}{mc} = \dfrac{1\,200\ \text{J}}{0.050\,0\ \text{kg}(387\ \text{J/kg}\ {}^\circ\text{C})} = 62.0^\circ\text{C}$

Thus, the final temperature is $\boxed{87.0^\circ\text{C}}$

**P17.4** We imagine the stone energy reservoir has a large area in contact with air and is always at nearly the same temperature as the air. Its overnight loss of energy is described by

$$\mathcal{P} = \frac{Q}{\Delta t} = \frac{mc\Delta T}{\Delta t}$$

$$m = \frac{\mathcal{P}\Delta t}{c\Delta T} = \frac{(-6\,000\ \text{J/s})(14\ \text{h})(3\,600\ \text{s/h})}{(850\ \text{J/kg}\ {}^\circ\text{C})(18^\circ\text{C} - 38^\circ\text{C})} = \frac{3.02\times 10^8\ \text{J kg}\cdot{}^\circ\text{C}}{850\ \text{J}(20^\circ\text{C})} = \boxed{1.78\times 10^4\ \text{kg}}$$

**P17.5**

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

$$(mc\Delta T)_{\text{water}} = -(mc\Delta T)_{\text{iron}}$$

$$20.0\text{ kg}(4\,186\text{ J/kg}\cdot°\text{C})(T_f - 25.0°\text{C}) = -(1.50\text{ kg})(448\text{ J/kg}\cdot°\text{C})(T_f - 600°\text{C})$$

$$T_f = \boxed{29.6°\text{C}}$$

***P17.6** Let us find the energy transferred in one minute.

$$Q = \left[m_{\text{cup}}c_{\text{cup}} + m_{\text{water}}c_{\text{water}}\right]\Delta T$$

$$Q = \left[(0.200\text{ kg})(900\text{ J/kg}\cdot°\text{C}) + (0.800\text{ kg})(4\,186\text{ J/kg}\cdot°\text{C})\right](-1.50°\text{C}) = -5\,290\text{ J}$$

If this much energy is removed from the system each minute, the rate of removal is

$$\mathcal{P} = \frac{|Q|}{\Delta t} = \frac{5\,290\text{ J}}{60.0\text{ s}} = 88.2\text{ J/s} = \boxed{88.2\text{ W}}.$$

***P17.7** (a) Work that the bit does in deforming the block, breaking chips off, and giving them kinetic energy is not a final destination for energy. All of this work turns entirely into internal energy as soon as the chips stop their macroscopic motion. The amount of energy input to the steel is the work done by the bit:

$$W = \vec{\mathbf{F}}\cdot\vec{\mathbf{d}} = (3.2\text{ N})(40\text{ m/s})(15\text{ s})\cos 0° = 1\,920\text{ J}$$

To evaluate the temperature change produced by this energy we imagine injecting the same quantity of energy as heat from a stove. The bit, chips, and block all undergo the same temperature change. Any difference in temperature between one bit of steel and another would erase itself by causing a heat transfer from the temporarily hotter to the colder region.

$$Q = mc\Delta T$$

$$\Delta T = \frac{Q}{mc} = \frac{1\,920\text{ J}\cdot\text{kg}\cdot°\text{C}}{(0.267\text{ kg})(448\text{ J})} = \boxed{16.1°\text{C}}$$

(b) See part (a).

**P17.8** (a)

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

$$(m_w c_w + m_c c_c)(T_f - T_c) = -m_{\text{Cu}}c_{\text{Cu}}(T_f - T_{\text{Cu}}) - m_{unk}c_{unk}(T_f - T_{unk})$$

where $w$ is for water, $c$ the calorimeter, Cu the copper sample, and *unk* the unknown.

$$\left[250\text{ g}(1.00\text{ cal/g}\cdot°\text{C}) + 100\text{ g}(0.215\text{ cal/g}\cdot°\text{C})\right](20.0 - 10.0)°\text{C}$$

$$= -(50.0\text{ g})(0.092\,4\text{ cal/g}\cdot°\text{C})(20.0 - 80.0)°\text{C} - (70.0\text{ g})c_{unk}(20.0 - 100)°\text{C}$$

$$2.44\times10^3\text{ cal} = \left(5.60\times10^3\text{ g}\cdot°\text{C}\right)c_{unk}$$

or $c_{unk} = \boxed{0.435\text{ cal/g}\cdot°\text{C}}$.

(b) The material of the sample can be $\boxed{\text{beryllium}}$.

***P17.9** We do not know whether the aluminum will rise or drop in temperature. The energy the water can absorb in rising to 26°C is $mc\Delta T = 0.25\text{ kg }4\,186\dfrac{\text{J}}{\text{kg °C}}6\text{°C} = 6\,279\text{ J}$. The energy the copper can put out in dropping to 26°C is $mc\Delta T = 0.1\text{ kg }387\dfrac{\text{J}}{\text{kg °C}}74\text{°C} = 2\,864\text{ J}$. Since $6\,279\text{ J} > 2\,864\text{ J}$, the final temperature is less than 26°C. We can write $Q_h = -Q_c$ as

$$Q_{\text{water}} + Q_{\text{Al}} + Q_{\text{Cu}} = 0$$

$$0.25\text{ kg }4\,186\frac{\text{J}}{\text{kg °C}}\left(T_f - 20\text{°C}\right) + 0.4\text{ kg }900\frac{\text{J}}{\text{kg °C}}\left(T_f - 26\text{°C}\right)$$

$$+0.1\text{ kg }387\frac{\text{J}}{\text{kg °C}}\left(T_f - 100\text{°C}\right) = 0$$

$$1\,046.5T_f - 20\,930\text{°C} + 360T_f - 9\,360\text{°C} + 38.7T_f - 3\,870\text{°C} = 0$$

$$1\,445.2T_f = 34\,160\text{°C}$$

$$T_f = \boxed{23.6\text{°C}}$$

**P17.10** $Q_{\text{cold}} = -Q_{\text{hot}}$

$$m_{\text{Al}}c_{\text{Al}}\left(T_f - T_c\right) + m_c c_w\left(T_f - T_c\right) = -m_h c_w\left(T_f - T_h\right)$$

$$(m_{\text{Al}}c_{\text{Al}} + m_c c_w)T_f - (m_{\text{Al}}c_{\text{Al}} + m_c c_w)T_c = -m_h c_w T_f + m_h c_w T_h$$

$$(m_{\text{Al}}c_{\text{Al}} + m_c c_w + m_h c_w)T_f = (m_{\text{Al}}c_{\text{Al}} + m_c c_w)T_c + m_h c_w T_h$$

$$T_f = \boxed{\frac{(m_{\text{Al}}c_{\text{Al}} + m_c c_w)T_c + m_h c_w T_h}{m_{\text{Al}}c_{\text{Al}} + m_c c_w + m_h c_w}}$$

## Section 17.3 Latent Heat and Phase Changes

**P17.11** The heat needed is the sum of the following terms:

$$Q_{\text{needed}} = (\text{heat to reach melting point}) + (\text{heat to melt})$$

$$+(\text{heat to reach boiling point}) + (\text{heat to vaporize}) + (\text{heat to reach }110\text{°C})$$

Thus, we have

$$Q_{\text{needed}} = 0.040\,0\text{ kg}\Big[(2\,090\text{ J/kg °C})(10.0\text{°C}) + \left(3.33\times10^5\text{ J/kg}\right)$$

$$+(4\,186\text{ J/kg °C})(100\text{°C}) + \left(2.26\times10^6\text{ J/kg}\right) + (2\,010\text{ J/kg °C})(10.0\text{°C})\Big]$$

$$Q_{\text{needed}} = \boxed{1.22\times10^5\text{ J}}$$

**P17.12** $Q_{\text{cold}} = -Q_{\text{hot}}$

$$(m_w c_w + m_c c_c)(T_f - T_i) = -m_s\left[-L_v + c_w(T_f - 100)\right]$$

$$\left[0.250\text{ kg}(4\,186\text{ J/kg}\cdot{}^\circ\text{C}) + 0.050\,0\text{ kg}(387\text{ J/kg}\cdot{}^\circ\text{C})\right](50.0^\circ\text{C} - 20.0^\circ\text{C})$$

$$= -m_s\left[-2.26\times10^6\text{ J/kg} + (4\,186\text{ J/kg}\cdot{}^\circ\text{C})(50.0^\circ\text{C} - 100^\circ\text{C})\right]$$

$$m_s = \frac{3.20\times10^4\text{ J}}{2.47\times10^6\text{ J/kg}} = 0.012\,9\text{ kg} = \boxed{12.9\text{ g steam}}$$

**P17.13** The bullet will not melt all the ice, so its final temperature is 0°C.

Then $\left(\frac{1}{2}mv^2 + mc|\Delta T|\right)_{\text{bullet}} = m_w L_f$

where $m_w$ is the melt water mass

$$m_w = \frac{0.500(3.00\times10^{-3}\text{ kg})(240\text{ m/s})^2 + 3.00\times10^{-3}\text{ kg}(128\text{ J/kg}\cdot{}^\circ\text{C})(30.0^\circ\text{C})}{3.33\times10^5\text{ J/kg}}$$

$$m_w = \frac{86.4\text{ J} + 11.5\text{ J}}{333\,000\text{ J/kg}} = \boxed{0.294\text{ g}}$$

**P17.14** $Q = m_{\text{Cu}}c_{\text{Cu}}\Delta T = m_{\text{N}_2}\left(L_{\text{vap}}\right)_{\text{N}_2}$

$$1.00\text{ kg}(0.092\,0\text{ cal/g}\cdot{}^\circ\text{C})(293 - 77.3)^\circ\text{C} = m(48.0\text{ cal/g})$$

$$m = \boxed{0.414\text{ kg}}$$

**P17.15** (a) Since the heat required to melt 250 g of ice at 0°C *exceeds* the heat required to cool 600 g of water from 18°C to 0°C, the final temperature of the system (water + ice) must be $\boxed{0^\circ\text{C}}$.

(b) Let $m$ represent the mass of ice that melts before the system reaches equilibrium at 0°C.

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

$$mL_f = -m_w c_w(0^\circ\text{C} - T_i)$$

$$m(3.33\times10^5\text{ J/kg}) = -(0.600\text{ kg})(4\,186\text{ J/kg}\cdot{}^\circ\text{C})(0^\circ\text{C} - 18.0^\circ\text{C})$$

$$m = 136\text{ g, so the ice remaining} = 250\text{ g} - 136\text{ g} = \boxed{114\text{ g}}$$

**P17.16** The original gravitational energy of the hailstone-Earth system changes entirely into additional internal energy in the hailstone, to produce its phase change. No temperature change occurs, either in the hailstone, in the air, or in sidewalk. Then

$$mgy = mL$$

$$y = \frac{L}{g} = \frac{3.33\times10^5\text{ J/kg}}{9.8\text{ m/s}^2}\left(\frac{1\text{ kg}\cdot\text{m}^2/\text{s}^2}{1\text{ J}}\right) = \boxed{3.40\times10^4\text{ m}}$$

***P17.17** The original kinetic energy all becomes thermal energy:

$$\frac{1}{2}mv^2+\frac{1}{2}mv^2=2\left(\frac{1}{2}\right)\left(5.00\times10^{-3}\text{ kg}\right)\left(500\text{ m/s}\right)^2=1.25\text{ kJ}$$

Raising the temperature to the melting point requires

$$Q=mc\Delta T=10.0\times10^{-3}\text{ kg}(128\text{ J/kg °C})(327\text{°C}-20.0\text{°C})=393\text{ J}$$

Since $1\,250\text{ J}>393\text{ J}$, the lead starts to melt. Melting it all requires

$$Q=mL=\left(10.0\times10^{-3}\text{ kg}\right)\left(2.45\times10^{4}\text{ J/kg}\right)=245\text{ J}$$

Since $1\,250\text{ J}>393+245\text{ J}$, it all melts. If we assume $\boxed{\text{liquid lead}}$ has the same specific heat as solid lead, the final temperature is given by

$$1.25\times10^{3}\text{ J}=393\text{ J}+245\text{ J}+10.0\times10^{-3}\text{ kg}(128\text{ J/kg °C})\left(T_f-327\text{°C}\right)$$

$$\boxed{T_f=805\text{°C}}$$

**P17.18** We find the quantity of water vapor in one exhaled breath

$$PV=nRT:\qquad n=\frac{PV}{RT}=\frac{\left(3.20\times10^{3}\text{ N/m}^2\right)\left(0.600\times10^{-3}\text{ m}^3\right)}{(8.314\text{ J/mol·K})(273\text{ K}+37\text{ K})}=7.45\times10^{-4}\text{ mol}$$

The molar mass of water ($H_2O$) is $M=\left(2(1.00)+16.0\right)\text{ g/mol}=0.018\,0\text{ kg/mol}$. The mass of water vapor exhaled in one breath is $m_{\text{sample}}=nM=7.45\times10^{-4}\text{ mol}(0.0180\text{ kg/mol})=1.34\times10^{-5}\text{ kg}$. The energy absorbed from your body as the water evaporates can be estimate as

$$Q=mL=1.34\times10^{-5}\text{ kg}\left(2.26\times10^{6}\text{ J/kg}\right)=30.3\text{ J}$$

Your rate of energy loss is $\mathcal{P}=\frac{Q}{\Delta t}=\frac{30.3\text{ J}}{\text{breath}}\left(\frac{22.0\text{ breath}}{\text{min}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)=\boxed{11.1\text{ W}}$ Note that a dog does not perspire. Instead, the dog pants, maximizes energy loss through the pathway considered here.

## Section 17.4 Work in Thermodynamic Processes

**P17.19** $W_{if} = -\int_i^f P\,dV$

The work done on the gas is the negative of the area under the curve $P = \alpha V^2$ between $V_i$ and $V_f$.

$$W_{if} = -\int_i^f \alpha V^2 dV = -\frac{1}{3}\alpha\left(V_f^3 - V_i^3\right)$$

$$V_f = 2V_i = 2\left(1.00\text{ m}^3\right) = 2.00\text{ m}^3$$

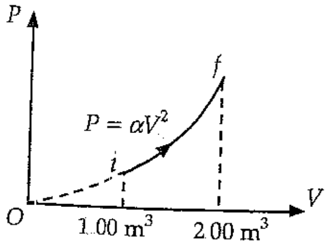

FIG. P17.19

$$W_{if} = -\frac{1}{3}\left[\left(5.00\text{ atm/m}^6\right)\left(1.013\times 10^5\text{ Pa/atm}\right)\right]\left[\left(2.00\text{ m}^3\right)^3 - \left(1.00\text{ m}^3\right)^3\right] = \boxed{-1.18\text{ MJ}}$$

**P17.20** (a) $W = -\int P\,dV$

$$W = -\left(6.00\times 10^6\text{ Pa}\right)(2.00-1.00)\text{ m}^3 +$$
$$-\left(4.00\times 10^6\text{ Pa}\right)(3.00-2.00)\text{ m}^3 +$$
$$-\left(2.00\times 10^6\text{ Pa}\right)(4.00-3.00)\text{ m}^3$$
$$W_{i\to f} = \boxed{-12.0\text{ MJ}}$$

(b) $W_{f\to i} = \boxed{+12.0\text{ MJ}}$

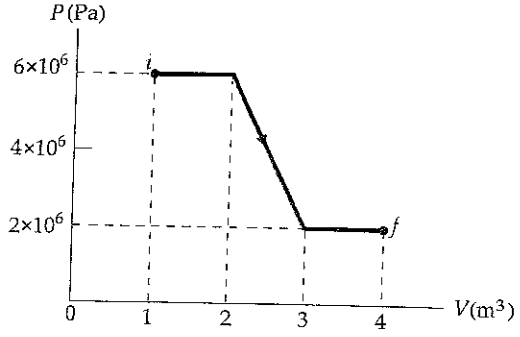

FIG. P17.20

**P17.21** $W = -P\Delta V = -P\left(\frac{nR}{P}\right)\left(T_f - T_i\right) = -nR\Delta T = -(0.200)(8.314)(280) = \boxed{-466\text{ J}}$

**P17.22** $W = -\int_i^f P\,dV = -P\int_i^f dV = -P\Delta V = -nR\Delta T = \boxed{-nR(T_2 - T_1)}$ The negative sign indicates that the expanding gas does positive work. The quantity of work is directly proportional to the quantity of gas and to the temperature change.

## Section 17.5 The First Law of Thermodynamics

**P17.23** $\Delta E_{\text{int}} = Q + W$

$$Q = \Delta E_{\text{int}} - W = -500\text{ J} - 220\text{ J} = \boxed{-720\text{ J}}$$

The negative sign indicates that positive energy is transferred *from* the system by heat.

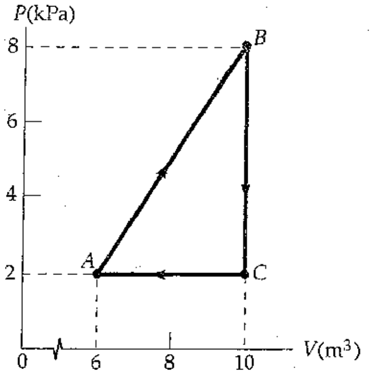

FIG. P17.24

**P17.24** (a) $Q = -W =$ Area of triangle

$$Q = \frac{1}{2}\left(4.00\text{ m}^3\right)(6.00\text{ kPa}) = \boxed{12.0\text{ kJ}}$$

(b) $Q = -W = \boxed{-12.0\text{ kJ}}$

**P17.25**

| | $Q$ | $W$ | $\Delta E_{\text{int}}$ | |
|---|---|---|---|---|
| $BC$ | – | 0 | – | $(Q = \Delta E_{\text{int}}$ since $W_{BC} = 0)$ |
| $CA$ | – | + | – | $(\Delta E_{\text{int}} < 0$ and $W > 0$, so $Q < 0)$ |
| $AB$ | + | – | + | $(W < 0,\ \Delta E_{\text{int}} > 0$ since $\Delta E_{\text{int}} < 0$ for $B \to C \to A$; so $Q > 0)$ |

## Section 17.6 Some Applications of the First Law of Thermodynamics

**P17.26** (a)
$$W = -nRT\ln\left(\frac{V_f}{V_i}\right) = -P_fV_f\ln\left(\frac{V_f}{V_i}\right)$$

$$\text{so } V_i = V_f\exp\left(+\frac{W}{P_fV_f}\right) = (0.025\,0)\exp\left[\frac{-3\,000}{0.025\,0\left(1.013\times10^5\right)}\right] = \boxed{0.007\,65\text{ m}^3}$$

(b)
$$T_f = \frac{P_fV_f}{nR} = \frac{1.013\times10^5\text{ Pa}\left(0.025\,0\text{ m}^3\right)}{1.00\text{ mol}(8.314\text{ J/K mol})} = \boxed{305\text{ K}}$$

**P17.27** (a) $\Delta E_{\text{int}} = Q - P\Delta V = 12.5\text{ kJ} - 2.50\text{ kPa}(3.00 - 1.00)\text{ m}^3 = \boxed{7.50\text{ kJ}}$

(b)
$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$
$$T_2 = \frac{V_2}{V_1}T_1 = \frac{3.00}{1.00}(300\text{ K}) = \boxed{900\text{ K}}$$

**P17.28** (a)
$$W = -P\Delta V = -P[3\alpha V\Delta T]$$
$$= -\left(1.013\times10^5\text{ N/m}^2\right)\left[3\left(24.0\times10^{-6}\,{}^\circ\text{C}^{-1}\right)\left(\frac{1.00\text{ kg}}{2.70\times10^3\text{ kg/m}^3}\right)(18.0^\circ\text{C})\right]$$
$$W = \boxed{-48.6\text{ mJ}}$$

(b) $Q = cm\Delta T = (900\text{ J/kg}\,^\circ\text{C})(1.00\text{ kg})(18.0^\circ\text{C}) = \boxed{16.2\text{ kJ}}$

(c) $\Delta E_{\text{int}} = Q + W = 16.2\text{ kJ} - 48.6\text{ mJ} = \boxed{16.2\text{ kJ}}$

**P17.29** $$W=-P\Delta V=-P(V_s-V_w)=-\frac{P(nRT)}{P}+P\left[\frac{18.0\text{ g}}{\left(1.00\text{ g/cm}^3\right)\left(10^6\text{ cm}^3/\text{m}^3\right)}\right]$$

$$W=-(1.00\text{ mol})(8.314\text{ J/K}\cdot\text{mol})(373\text{ K})+\left(1.013\times10^5\text{ N/m}^2\right)\left(\frac{18.0\text{ g}}{10^6\text{ g/m}^3}\right)=\boxed{-3.10\text{ kJ}}$$

$$Q=mL_v=0.0180\text{ kg}\left(2.26\times10^6\text{ J/kg}\right)=40.7\text{ kJ}$$

$$\Delta E_{\text{int}}=Q+W=\boxed{37.6\text{ kJ}}$$

**P17.30** (a) The work done during each step of the cycle equals the negative of the area under that segment of the *PV* curve.

$$W=W_{DA}+W_{AB}+W_{BC}+W_{CD}$$

$$W=-P_i(V_i-3V_i)+0-3P_i(3V_i-V_i)+0=\boxed{-4P_iV_i}$$

(b) The initial and final values of *T* for the system are equal. Therefore, $\Delta E_{\text{int}}=0$ and $Q=-W=\boxed{4P_iV_i}$

(c) $W=-4P_iV_i=-4nRT_i=-4(1.00)(8.314)(273)=\boxed{-9.08\text{ kJ}}$

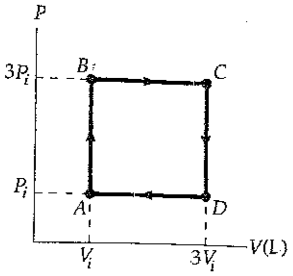

**FIG. P17.30**

**P17.31** (a) $P_iV_i=P_fV_f=nRT=2.00\text{ mol}(8.314\text{ J/K mol})(300\text{ K})=4.99\times10^3\text{ J}$

$$V_i=\frac{nRT}{P_i}=\frac{4.99\times10^3\text{ J}}{0.400\text{ atm}}$$

$$V_f=\frac{nRT}{P_f}=\frac{4.99\times10^3\text{ J}}{1.20\text{ atm}}=\frac{1}{3}V_i=\boxed{0.0410\text{ m}^3}$$

(b) $W=-\int P\,dV=-nRT\ln\left(\frac{V_f}{V_i}\right)=-\left(4.99\times10^3\right)\ln\left(\frac{1}{3}\right)=\boxed{+5.48\text{ kJ}}$

(c) $\Delta E_{\text{int}}=0=Q+W$

$Q=\boxed{-5.48\text{ kJ}}$

**P17.32** $\Delta E_{\text{int},ABC}=\Delta E_{\text{int},AC}$ (conservation of energy)

(a) $\Delta E_{\text{int},ABC}=Q_{ABC}+W_{ABC}$ (First Law)

$Q_{ABC}=800\text{ J}+500\text{ J}=\boxed{1\,300\text{ J}}$

(b) $W_{CD}=-P_C\Delta V_{CD}$, $\Delta V_{AB}=-\Delta V_{CD}$, and $P_A=5P_C$

Then, $W_{CD}=\frac{1}{5}P_A\Delta V_{AB}=-\frac{1}{5}W_{AB}=\boxed{100\text{ J}}$

(+ means that work is done on the system)

(c) $W_{CDA}=W_{CD}$ so that $Q_{CA}=\Delta E_{\text{int},CA}-W_{CDA}=-800\text{ J}-100\text{ J}=\boxed{-900\text{ J}}$

(− means that energy must be removed from the system by heat)

(d) $\Delta E_{\text{int},CD}=\Delta E_{\text{int},CDA}-\Delta E_{\text{int},DA}=-800\text{ J}-500\text{ J}=-1\,300\text{ J}$

and $Q_{CD}=\Delta E_{\text{int},CD}-W_{CD}=-1\,300\text{ J}-100\text{ J}=\boxed{-1\,400\text{ J}}$

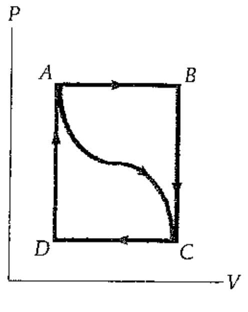

**FIG. P17.32**

## Section 17.7 Molar Specific Heats of Ideal Gases

**P17.33** We use the tabulated values for $C_p$ and $C_V$.

(a) $$Q = nC_p\Delta T = 1.00\text{ mol}(28.8\text{ J/mol K})(420-300)\text{K} = \boxed{3.46\text{ kJ}}$$

(b) $$\Delta E_{\text{int}} = nC_V\Delta T = 1.00\text{ mol}(20.4\text{ J/mol}\cdot\text{K})(120\text{ K}) = \boxed{2.45\text{ kJ}}$$

(c) $$W = -Q + \Delta E_{\text{int}} = -3.46\text{ kJ} + 2.45\text{ kJ} = \boxed{-1.01\text{ kJ}}$$

**P17.34** $$E_{\text{int}} = \frac{3}{2}nRT$$

$$\Delta E_{\text{int}} = \frac{3}{2}nR\Delta T = \frac{3}{2}(3.00\text{ mol})(8.314\text{ J/mol K})(2.00\text{ K}) = \boxed{74.8\text{ J}}$$

**P17.35** $n = 1.00\text{ mol}$, $T_i = 300\text{ K}$

(b) Since $V = \text{constant}$, $W = \boxed{0}$.

(a) $$\Delta E_{\text{int}} = Q + W = 209\text{ J} + 0 = \boxed{209\text{ J}}$$

(c) $$\Delta E_{\text{int}} = nC_V\Delta T = n\left(\frac{3}{2}R\right)\Delta T \text{ so}$$

$$\Delta T = \frac{2\Delta E_{\text{int}}}{3nR} = \frac{2(209\text{ J})}{3(1.00\text{ mol})(8.314\text{ J/mol}\cdot\text{K})} = 16.8\text{ K}$$

$$T = T_i + \Delta T = 300\text{ K} + 16.8\text{ K} = \boxed{317\text{ K}}$$

**P17.36** (a) $$C_V = \frac{5}{2}R = \frac{5}{2}(8.314\text{ J/mol}\cdot\text{K})\left(\frac{1.00\text{ mol}}{0.0289\text{ kg}}\right) = 719\text{ J/kg}\cdot\text{K} = \boxed{0.719\text{ kJ/kg}\cdot\text{K}}$$

(b) $$m = Mn = M\left(\frac{PV}{RT}\right)$$

$$m = (0.0289\text{ kg/mol})\left(\frac{200\times10^3\text{ Pa}\left(0.350\text{ m}^3\right)}{(8.314\text{ J/mol}\cdot\text{K})(300\text{ K})}\right) = \boxed{0.811\text{ kg}}$$

(c) We consider a constant volume process where no work is done.

$$Q = mC_V\Delta T = 0.811\text{ kg}(0.719\text{ kJ/kg K})(700\text{ K} - 300\text{ K}) = \boxed{233\text{ kJ}}$$

(d) We now consider a constant pressure process where the internal energy of the gas is increased and work is done

$$Q = mC_P\Delta T = m(C_V + R)\Delta T = m\left(\frac{7R}{2}\right)\Delta T = m\left(\frac{7C_V}{5}\right)\Delta T$$

$$Q = 0.811\text{ kg}\left[\frac{7}{5}(0.719\text{ kJ/kg}\cdot\text{K})\right](400\text{ K}) = \boxed{327\text{ kJ}}$$

**P17.37** Consider 800 cm$^3$ of (flavored) water at 90.0 °C mixing with 200 cm$^3$ of diatomic ideal gas at 20.0°C: $Q_{\text{cold}} = -Q_{\text{hot}}$ or

$$m_{\text{air}} c_{P,\text{air}} \left(T_f - T_{i,\text{air}}\right) = -m_w c_w (\Delta T)_w$$

$$(\Delta T)_w = \frac{-m_{\text{air}} c_{P,\text{air}} \left(T_f - T_{i,\text{air}}\right)}{m_w c_w} = \frac{-(\rho V)_{\text{air}} c_{P,\text{air}} (90.0°\text{C} - 20.0°\text{C})}{(\rho_w V_w) c_w}$$

where we have anticipated that the final temperature of the mixture will be close to 90.0°C. The molar specific heat of air is $C_{P,\text{ air}} = \frac{7}{2} R$ So the specific heat per gram is

$$c_{P\text{ air}} = \frac{7}{2}\left(\frac{R}{M}\right) = \frac{7}{2}(8.314 \text{ J/mol}\cdot\text{K})\left(\frac{1.00 \text{ mol}}{28.9 \text{ g}}\right) = 1.01 \text{ J/g }°\text{C}$$

$$(\Delta T)_w = -\frac{[(1.20\times 10^{-3} \text{ g/cm}^3)(200 \text{ cm}^3)](1.01 \text{ J/g}\cdot°\text{C})(70.0°\text{C})}{[(1.00 \text{ g/cm}^3)(800 \text{ cm}^3)](4\,186 \text{ J/kg}\cdot°\text{C})}$$

or $(\Delta T)_w = -5.05\times 10^{-3}\,°\text{C}$. The change of temperature for the water is $\boxed{\text{between } 10^{-3}\,°\text{C and } 10^{-2}\,°\text{C}}$.

***P17.38** (a) The air is far from liquefaction so it behaves as an ideal gas. From $PV = nRT$ we have $PV = \frac{m}{M}RT$, $PM = \frac{m}{V}RT = \rho RT$. For the samples of air in the balloon at 10°C (cold) and at the elevated temperature (hot) we have $PM = \rho_c R T_c$ and $PM = \rho_h R T_h$. Then $\rho_h T_h = \rho_c T_c$ and $\rho_h = \frac{\rho_c T_c}{T_h}$. For equilibrium of the balloon on the point of rising,

$$\sum F_y = ma_y \qquad +B - F_{g\text{ hot air}} - F_{g\text{ cargo}} = 0$$

$$+\rho_c V g - \rho_h V g - mg = 0$$

$$+\rho_c V - \frac{\rho_c T_c}{T_h} V - m = 0$$

$$\left(1.25 \text{ kg/m}^3\right) 400 \text{ m}^3 - \left(1.25 \text{ kg/m}^3\right)\frac{283 \text{ K}}{T_h} 400 \text{ m}^3 - 200 \text{ kg} = 0$$

$$300 \text{ kg} = 500 \text{ kg}\frac{283 \text{ K}}{T_h}$$

$$T_h = \frac{500}{300} 283 \text{ K} = 472 \text{ K}$$

The quantity of air that must be warmed is given by $PV = n_h R T_h$, $n_h = \frac{PV}{RT_h}$. The heat input required is

$$Q = nC_p \Delta T = \frac{PV}{RT_h}\,\frac{7}{2}R(T_h - T_c) = \frac{101\times 10^3 \text{N } 400 \text{ m}^3 \text{ } 7(472 \text{ K} - 283 \text{ K})}{\text{m}^2 \text{ } 472 \text{ K } 2} = \boxed{5.66\times 10^7 \text{ J}}$$

(b) $Q = mH$, $m = \frac{Q}{H} = \frac{5.66\times 10^7 \text{ J}}{5.03\times 10^7 \text{ J/kg}} = \boxed{1.12 \text{ kg}}$

**P17.39** $Q = (nC_P\Delta T)_{\text{isobaric}} + (nC_V\Delta T)_{\text{isovolumetric}}$

In the isobaric process, $V$ doubles so $T$ must double, to $2T_i$

In the isovolumetric process, $P$ triples so $T$ changes from $2T_i$ to $6T_i$

$$Q = n\left(\frac{7}{2}R\right)(2T_i - T_i) + n\left(\frac{5}{2}R\right)(6T_i - 2T_i) = 13.5nRT_i = \boxed{13.5PV}$$

---

## Section 17.8 Adiabatic Processes for an Ideal Gas

**P17.40** (a) $P_iV_i^{\gamma} = P_fV_f^{\gamma}$ so $\dfrac{V_f}{V_i} = \left(\dfrac{P_i}{P_f}\right)^{1/\gamma} = \left(\dfrac{1.00}{20.0}\right)^{5/7} = \boxed{0.118}$

(b) $\dfrac{T_f}{T_i} = \dfrac{P_fV_f}{P_iV_i} = \left(\dfrac{P_f}{P_i}\right)\left(\dfrac{V_f}{V_i}\right) = (20.0)(0.118)$, $\dfrac{T_f}{T_i} = \boxed{2.35}$

(c) Since the process is adiabatic, $\boxed{Q = 0}$

Since $\gamma = 1.40 = \dfrac{C_P}{C_V} = \dfrac{R + C_V}{C_V}$, $C_V = \dfrac{5}{2}R$ and $\Delta T = 2.35T_i - T_i = 1.35T_i$

$$\Delta E_{\text{int}} = nC_V\Delta T = (0.0160\text{ mol})\left(\frac{5}{2}\right)(8.314\text{ J/mol}\cdot\text{K})\left[1.35(300\text{ K})\right] = \boxed{135\text{ J}}$$

and $W = -Q + \Delta E_{\text{int}} = 0 + 135\text{ J} = \boxed{+135\text{ J}}$

**P17.41** (a) $P_iV_i^{\gamma} = P_fV_f^{\gamma}$

$$P_f = P_i\left(\frac{V_i}{V_f}\right)^{\gamma} = 5.00\text{ atm}\left(\frac{12.0}{30.0}\right)^{1.40} = \boxed{1.39\text{ atm}}$$

(b)
$$T_i = \frac{P_iV_i}{nR} = \frac{5.00\left(1.013\times10^5\text{ Pa}\right)\left(12.0\times10^{-3}\text{ m}^3\right)}{2.00\text{ mol}(8.314\text{ J/mol}\cdot\text{K})} = \boxed{366\text{ K}}$$

$$T_f = \frac{P_fV_f}{nR} = \frac{1.39\left(1.013\times10^5\text{ Pa}\right)\left(30.0\times10^{-3}\text{ m}^3\right)}{2.00\text{ mol}(8.314\text{ J/mol}\cdot\text{K})} = \boxed{253\text{ K}}$$

(c) The process is adiabatic: $\boxed{Q = 0}$

$\gamma = 1.40 = \dfrac{C_P}{C_V} = \dfrac{R + C_V}{C_V}$, $C_V = \dfrac{5}{2}R$

$$\Delta E_{\text{int}} = nC_V\Delta T = 2.00\text{ mol}\left(\frac{5}{2}(8.314\text{ J/mol}\cdot\text{K})\right)(253\text{ K} - 365\text{ K}) = \boxed{-4.66\text{ kJ}}$$

$$W = \Delta E_{\text{int}} - Q = -4.66\text{ kJ} - 0 = \boxed{-4.66\text{ kJ}}$$

**P17.42** $$\frac{T_f}{T_i}=\left(\frac{V_i}{V_f}\right)^{\gamma-1}=\left(\frac{1}{2}\right)^{0.400}$$

If $T_i=300\text{ K}$, then $T_f=\boxed{227\text{ K}}$

**P17.43** (a) See the diagram at the right.

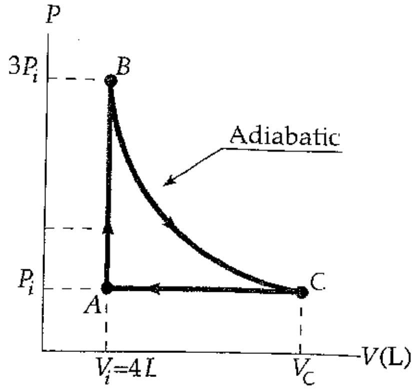

**FIG. P17.43**

(b)
$$P_BV_B{}^{\gamma}=P_CV_C{}^{\gamma}$$
$$3P_iV_i^{\gamma}=P_iV_C{}^{\gamma}$$
$$V_C=\left(3^{1/\gamma}\right)V_i=\left(3^{5/7}\right)V_i=2.19V_i$$
$$V_C=2.19(4.00\text{ L})=\boxed{8.77\text{ L}}$$

(c)
$$P_BV_B=nRT_B=3P_iV_i=3nRT_i$$
$$T_B=3T_i=3(300\text{ K})=\boxed{900\text{ K}}$$

(d) After one whole cycle, $T_A=T_i=\boxed{300\text{ K}}$

(e) In $AB$, $Q_{AB}=nC_V\Delta V=n\left(\frac{5}{2}R\right)(3T_i-T_i)=(5.00)nRT_i$, $Q_{BC}=0$ as this process is adiabatic

$P_CV_C=nRT_C=P_i(2.19V_i)=(2.19)nRT_i$ so $T_C=2.19T_i$,

$$Q_{CA}=nC_P\Delta T=n\left(\frac{7}{2}R\right)(T_i-2.19T_i)=(-4.17)nRT_i$$

For the whole cycle,

$$Q_{ABCA}=Q_{AB}+Q_{BC}+Q_{CA}=(5.00-4.17)nRT_i=(0.829)nRT_i$$
$$(\Delta E_{\text{int}})_{ABCA}=0=Q_{ABCA}+W_{ABCA}$$
$$W_{ABCA}=-Q_{ABCA}=-(0.829)nRT_i=-(0.829)P_iV_i$$
$$W_{ABCA}=-(0.829)\left(1.013\times10^{5}\text{ Pa}\right)\left(4.00\times10^{-3}\text{ m}^3\right)=\boxed{-336\text{ J}}$$

**P17.44** (a) The work done *on* the gas is

$$W_{ab} = -\int_{V_a}^{V_b} P\,dV$$

For the isothermal process,

$$W_{ab'} = -nRT_a \int_{V_a}^{V_b} \left(\frac{1}{V}\right) dV$$

$$W_{ab'} = -nRT_a \ln\left(\frac{V_{b'}}{V_a}\right) = nRT \ln\left(\frac{V_a}{V_{b'}}\right)$$

Thus,

$$W_{ab'} = 5.00 \text{ mol}(8.314 \text{ J/mol}\cdot\text{K})(293 \text{ K})\ln(10.0)$$

$$W_{ab'} = \boxed{28.0 \text{ kJ}}$$

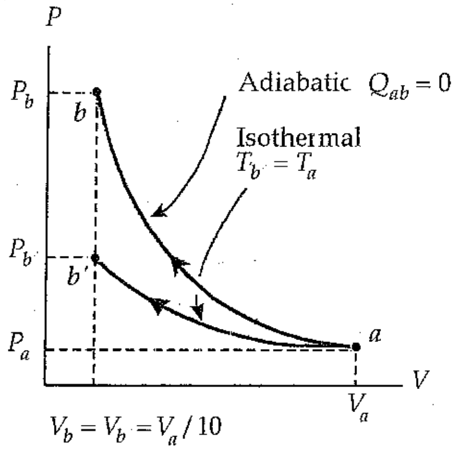

**FIG. P17.44**

(b) For the adiabatic process, we must first find the final temperature, $T_b$. Since air consists primarily of diatomic molecules, we shall use $\gamma_{\text{air}} = 1.40$ and $C_{V\,\text{air}} = \frac{5R}{2} = 5\frac{8.314}{2} = 20.8 \text{ J/mol}\cdot\text{K}$. Then, for the adiabatic process

$$T_b = T_a\left(\frac{V_a}{V_b}\right)^{\gamma-1} = 293 \text{ K}(10.0)^{0.400} = 736 \text{ K}.$$

Thus, the work done on the gas during the adiabatic process is

$$W_{ab} = \left(-Q + \Delta E_{\text{int}}\right)_{ab} = \left(-0 + nC_V\Delta T\right)_{ab} = nC_V\left(T_b - T_a\right)$$

or $W_{ab} = 5.00 \text{ mol}(20.8 \text{ J/mol}\cdot\text{K})(736 - 293) \text{ K} = \boxed{46.0 \text{ kJ}}$.

(c) For the isothermal process, we have $P_{b'}V_{b'} = P_aV_a$. Thus,

$P_{b'} = P_a\left(\frac{V_{a'}}{V_{b'}}\right) = 1.00 \text{ atm}(10.0) = \boxed{10.0 \text{ atm}}$. For the adiabatic process, we have $P_bV_b^{\gamma} = P_aV_a^{\gamma}$.

Thus, $P_b = P_a\left(\frac{V_a}{V_b}\right)^{\gamma} = 1.00 \text{ atm}(10.0)^{1.40} = \boxed{25.1 \text{ atm}}$.

**P17.45** We suppose the air plus burnt gasoline behaves like a diatomic ideal gas. We find its final absolute pressure:

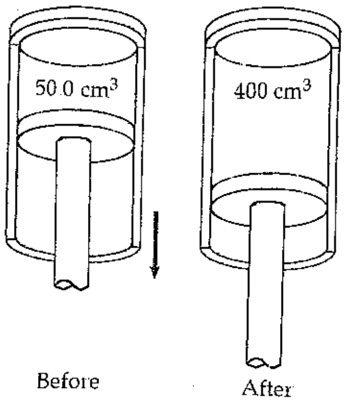

FIG. P17.45

$$21.0\text{ atm}\left(50.0\text{ cm}^3\right)^{7/5}=P_f\left(400\text{ cm}^3\right)^{7/5}$$

$$P_f=21.0\text{ atm}\left(\frac{1}{8}\right)^{7/5}=1.14\text{ atm}$$

Now $Q=0$

and $W=\Delta E_{\text{int}}=nC_V\left(T_f-T_i\right)$

$$\therefore W=\frac{5}{2}nRT_f-\frac{5}{2}nRT_i=\frac{5}{2}\left(P_fV_f-P_iV_i\right)$$

$$W=\frac{5}{2}\left[1.14\text{ atm}\left(400\text{ cm}^3\right)-21.0\text{ atm}\left(50.0\text{ cm}^3\right)\right]\left(\frac{1.013\times10^5\text{ N/m}^2}{1\text{ atm}}\right)\left(10^{-6}\text{ m}^3/\text{cm}^3\right)$$

$$W=-150\text{ J}$$

The output work is $-W=+150$ J. The time for this stroke is $\frac{1}{4}\left(\frac{1\text{ min}}{2500}\right)\left(\frac{60\text{ s}}{1\text{ min}}\right)=6.00\times10^{-3}$ s

$$\mathcal{P}=\frac{-W}{\Delta t}=\frac{150\text{ J}}{6.00\times10^{-3}\text{ s}}=\boxed{25.0\text{ kW}}$$

## Section 17.9 Molar Specific Heats and the Equipartition of Energy

**P17.46** (1) $E_{\text{int}}=Nf\left(\frac{k_BT}{2}\right)=f\left(\frac{nRT}{2}\right)$

(2) $C_V=\frac{1}{n}\left(\frac{dE_{\text{int}}}{dT}\right)=\frac{1}{2}fR$

(3) $C_P=C_V+R=\frac{1}{2}(f+2)R$

(4) $\gamma=\frac{C_P}{C_V}=\frac{f+2}{f}$

**P17.47** The heat capacity at constant volume is $nC_V$. An ideal gas of diatomic molecules has three degrees of freedom for translation in the $x$, $y$, and $z$ directions. If we take the $y$ axis along the axis of a molecule, then outside forces cannot excite rotation about this axis, since they have no lever arms. Collisions will set the molecule spinning only about the $x$ and $z$ axes.

(a) If the molecules do not vibrate, they have five degrees of freedom. Random collisions put equal amounts of energy $\frac{1}{2}k_BT$ into all five kinds of motion. The average energy of one molecule is $\frac{5}{2}k_BT$. The internal energy of the two-mole sample is

$$N\left(\frac{5}{2}k_BT\right)=nN_A\left(\frac{5}{2}k_BT\right)=n\left(\frac{5}{2}R\right)T=nC_VT.$$

The molar heat capacity is $C_V=\frac{5}{2}R$ and the sample's heat capacity is

$$nC_V=n\left(\frac{5}{2}R\right)=2\text{ mol}\left(\frac{5}{2}(8.314\text{ J/mol}\cdot\text{K})\right)$$

$$\boxed{nC_V=41.6\text{ J/K}}$$

For the heat capacity at constant pressure we have

$$nC_P=n(C_V+R)=n\left(\frac{5}{2}R+R\right)=\frac{7}{2}nR=2\text{ mol}\left(\frac{7}{2}(8.314\text{ J/mol}\cdot\text{K})\right)$$

$$\boxed{nC_P=58.2\text{ J/K}}$$

(b) In vibration with the center of mass fixed, both atoms are always moving in opposite directions with equal speeds. Vibration adds two more degrees of freedom for two more terms in the molecular energy, for kinetic and for elastic potential energy. We have $nC_V=n\left(\frac{7}{2}R\right)=\boxed{58.2\text{ J/K}}$ and $nC_P=n\left(\frac{9}{2}R\right)=\boxed{74.8\text{ J/K}}$.

## Section 17.10 Energy Transfer Mechanisms in Thermal Processes

**P17.48** $\mathcal{P}=kA\frac{\Delta T}{L}$

$$k=\frac{\mathcal{P}L}{A\Delta T}=\frac{10.0\text{ W}(0.0400\text{ m})}{1.20\text{ m}^2(15.0^\circ\text{C})}=\boxed{2.22\times10^{-2}\text{ W/m}\cdot{}^\circ\text{C}}$$

**P17.49** In the steady state condition, $\mathcal{P}_{\text{Au}} = \mathcal{P}_{\text{Ag}}$ so that

$$k_{\text{Au}} A_{\text{Au}} \left(\frac{\Delta T}{\Delta x}\right)_{\text{Au}} = k_{\text{Ag}} A_{\text{Ag}} \left(\frac{\Delta T}{\Delta x}\right)_{\text{Ag}}$$

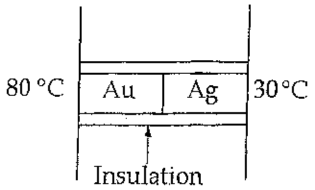

FIG. P17.49

In this case

$$A_{\text{Au}} = A_{\text{Ag}}$$
$$\Delta x_{\text{Au}} = \Delta x_{\text{Ag}}$$
$$\Delta T_{\text{Au}} = (80.0 - T)$$
$$\Delta T_{\text{Ag}} = (T - 30.0)$$

where $T$ is the temperature of the junction. Therefore, $k_{\text{Au}}(80.0 - T) = k_{\text{Ag}}(T - 30.0)$. And $\boxed{T = 51.2°\text{C}}$.

**P17.50** We suppose that the area of the transistor is so small that energy flow by heat from the transistor directly to the air is negligible compared to energy conduction through the mica.

$$\mathcal{P} = kA\frac{(T_h - T_c)}{L}$$

$$T_h = T_c + \frac{\mathcal{P}L}{kA} = 35.0°\text{C} + \frac{1.50\ \text{W}\left(0.0852 \times 10^{-3}\ \text{m}\right)}{(0.0753\ \text{W/m °C})(8.25 \times 6.25)\ 10^{-6}\ \text{m}^2} = \boxed{67.9°\text{C}}$$

**P17.51** $\mathcal{P} = \sigma A e T^4 = \left(5.67 \times 10^{-8}\ \text{W/m}^2\ \text{K}^4\right)\left[4\pi\left(6.96 \times 10^8\ \text{m}\right)^2\right](0.986)(5\ 800\ \text{K})^4$

$\mathcal{P} = \boxed{3.85 \times 10^{26}\ \text{W}}$

**P17.52** $\mathcal{P} = kA\dfrac{(T_h - T_c)}{L} = (0.210\ \text{W/m °C})\left(1.40\ \text{m}^2\right)\left(\dfrac{37.0°\text{C} - 34.0°\text{C}}{0.0250\ \text{m}}\right)$

$= 35.3\ \text{W} = (35.3\ \text{J/s})\left(\dfrac{1\ \text{kcal}}{4186\ \text{J}}\right)\left(\dfrac{3600\ \text{s}}{1\ \text{h}}\right) = \boxed{30.3\ \text{kcal/h}}$

Since this is much less than 240 kcal/h, blood flow is essential to cool the body.

**P17.53** The net rate of energy loss from his skin is

$$\mathcal{P}_{\text{net}} = \sigma A e\left(T^4 - T_0^{\,4}\right) = \left(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4\right)\left(1.50\ \text{m}^2\right)(0.900)\left[(308\ \text{K})^4 - (293\ \text{K})^4\right] = 125\ \text{W}.$$

Note that the temperatures must be in kelvins. The energy loss in ten minutes is

$$Q = \mathcal{P}_{\text{net}}\Delta t = (125\ \text{J/s})(600\ \text{s}) = \boxed{7.48 \times 10^4\ \text{J}}.$$

In the infrared, the person shines brighter than a hundred-watt light bulb.

## Section 17.11 Context Connection—Energy Balance for the Earth

**P17.54** We suppose the earth below is an insulator. The square meter must radiate in the infrared as much energy as it absorbs, $\mathcal{P} = \sigma A e T^4$. Assuming that $e = 1.00$ for blackbody blacktop:

$$1000\ \text{W} = \left(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4\right)\left(1.00\ \text{m}^2\right)(1.00)T^4$$

$T = \left(1.76 \times 10^{10}\ \text{K}^4\right)^{1/4} = \boxed{364\ \text{K}}$ (You can cook an egg on it.)

**P17.55** The sphere of radius $R$ absorbs sunlight over the area of its day hemisphere, projected as a flat circle perpendicular to the light: $\pi R^2$. It radiates in all directions, over area $4\pi R^2$. Then, in steady state,

$$\mathcal{P}_{\text{in}} = \mathcal{P}_{\text{out}}$$
$$e\left(1370\ \text{W/m}^2\right)\pi R^2 = e\sigma\left(4\pi R^2\right)T^4$$

The emissivity $e$, the radius $R$, and $\pi$ all cancel. Therefore,

$$T = \left[\frac{1370\ \text{W/m}^2}{4\left(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4\right)}\right]^{1/4} = \boxed{279\ \text{K}} = 6°\text{C}.$$

**P17.56** (a) Among atmospheric layers, $PV^{\gamma} = \text{constant}$ and $\dfrac{PV}{T} = \text{constant}$. Then $\left(P^{1/\gamma}\right)V = \text{constant}$ and $\dfrac{PV}{T\left(P^{1/\gamma}\right)V} = \text{constant}$. Then $T\left(P^{(1/\gamma)-1}\right) = T\left(P^{(1-\gamma)/\gamma}\right) = \text{constant}$

(b) We differentiate the equation $T\left(P^{(1/\gamma)-1}\right) = \text{constant}$ with respect to $y$:

$$T\left(\frac{1}{\gamma} - 1\right)\left(P^{(1/\gamma)-1-1}\right)\frac{dP}{dy} + \left(P^{(1/\gamma)-1}\right)\frac{dT}{dy} = 0$$

$$\frac{T}{P}\left(\frac{1}{\gamma} - 1\right)\frac{dP}{dy} + \frac{dT}{dy} = 0$$

$$\frac{dT}{dy} = \frac{T}{P}\left(1 - \frac{1}{\gamma}\right)\frac{dP}{dy}$$

(c) Substituting $\dfrac{dP}{dy} = -\rho g$ gives $\dfrac{dT}{dy} = \dfrac{T}{P}\left(1 - \dfrac{1}{\gamma}\right)(-\rho g)$. Now $\rho = \dfrac{m_{\text{sample}}}{V} = \dfrac{nM}{V}$. So

$$\frac{dT}{dy} = -\left(1 - \frac{1}{\gamma}\right)\frac{TnMg}{PV} = -\left(1 - \frac{1}{\gamma}\right)\frac{Mg}{R}$$

## Additional Problems

***P17.57** (a) The heat leaving the box during the day is given by $\mathcal{P} = kA\frac{(T_H - T_c)}{L} = \frac{Q}{\Delta t}$

$$Q = 0.012\frac{\text{W}}{\text{m}^\circ\text{C}}0.49\text{ m}^2\frac{37^\circ\text{C} - 23^\circ\text{C}}{0.045\text{ m}}12\text{ h}\left(\frac{3\,600\text{ s}}{1\text{ h}}\right) = 7.90\times10^4\text{ J}.$$

The heat lost at night is

$$Q = 0.012\frac{\text{W}}{\text{m}^\circ\text{C}}0.49\text{ m}^2\frac{37^\circ\text{C} - 16^\circ\text{C}}{0.045\text{ m}}12\text{ h}\left(\frac{3\,600\text{ s}}{1\text{ h}}\right) = 1.19\times10^5\text{ J}.$$

The total heat is $1.19\times10^5\text{ J} + 7.90\times10^4\text{ J} = 1.98\times10^5\text{ J}$. It must be supplied by the solidifying wax: $Q = mL$

$$m = \frac{Q}{L} = \frac{1.98\times10^5\text{ J}}{205\times10^3\text{ J/kg}} = \boxed{0.964\text{ kg or more}}$$

(b) The test samples and the inner surface of the insulation can be preheated to 37°C as the box is filled. If this is done, nothing changes in temperature during the test period. Then the masses of the test samples and the insulation make no difference.

**P17.58** The increase in internal energy required to melt 1.00 kg of snow is

$$\Delta E_{\text{int}} = (1.00\text{ kg})(3.33\times10^5\text{ J/kg}) = 3.33\times10^5\text{ J}$$

The force of friction is

$$f = \mu n = \mu mg = 0.200(75.0\text{ kg})(9.80\text{ m/s}^2) = 147\text{ N}$$

According to the problem statement, the loss of mechanical energy of the skier is assumed to be equal to the increase in internal energy of the snow. This increase in internal energy is

$$\Delta E_{\text{int}} = f\Delta r = (147\text{ N})\Delta r = 3.33\times10^5\text{ J}$$

and

$$\Delta r = \boxed{2.27\times10^3\text{ m}}.$$

**P17.59** (a) The energy thus far gained by the copper equals the energy loss by the silver. Your down parka is an excellent insulator.

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

or $$m_{\text{Cu}}c_{\text{Cu}}(T_f - T_i)_{\text{Cu}} = -m_{\text{Ag}}c_{\text{Ag}}(T_f - T_i)_{\text{Ag}}$$

$$(9.00\text{ g})(387\text{ J/kg}\cdot^\circ\text{C})(16.0^\circ\text{C}) = -(14.0\text{ g})(234\text{ J/kg}\cdot^\circ\text{C})(T_f - 30.0^\circ\text{C})_{\text{Ag}}$$

$$(T_f - 30.0^\circ\text{C})_{\text{Ag}} = -17.0^\circ\text{C}$$

so $$T_{f,\text{Ag}} = \boxed{13.0^\circ\text{C}}.$$

*continued on next page*

(b) Differentiating the energy gain-and-loss equation gives: $m_{\text{Ag}}c_{\text{Ag}}\left(\frac{dT}{dt}\right)_{\text{Ag}} = -m_{\text{Cu}}c_{\text{Cu}}\left(\frac{dT}{dt}\right)_{\text{Cu}}$

$$\left(\frac{dT}{dt}\right)_{\text{Ag}} = -\frac{m_{\text{Cu}}c_{\text{Cu}}}{m_{\text{Ag}}c_{\text{Ag}}}\left(\frac{dT}{dt}\right)_{\text{Cu}} = -\frac{9.00\text{ g}(387\text{ J/kg}\,^\circ\text{C})}{14.0\text{ g}(234\text{ J/kg}\,^\circ\text{C})}(+0.500\,^\circ\text{C/s})$$

$$\left(\frac{dT}{dt}\right)_{\text{Ag}} = \boxed{-0.532\,^\circ\text{C/s}}\ \text{(negative sign} \Rightarrow \text{decreasing temperature)}$$

**P17.60** (a) Before conduction has time to become important, the energy lost by the rod equals the energy gained by the helium. Therefore,

$$(mL_v)_{\text{He}} = (mc|\Delta T|)_{\text{Al}}$$

or $$(\rho VL_v)_{\text{He}} = (\rho Vc|\Delta T|)_{\text{Al}}$$

so $$V_{\text{He}} = \frac{(\rho Vc|\Delta T|)_{\text{Al}}}{(\rho L_v)_{\text{He}}}$$

$$V_{\text{He}} = \frac{(2.70\text{ g/cm}^3)(62.5\text{ cm}^3)(0.210\text{ cal/g}\cdot{}^\circ\text{C})(295.8\,^\circ\text{C})}{(0.125\text{ g/cm}^3)(2.09\times10^4\text{ J/kg})(1.00\text{ cal/4.186 J})(1.00\text{ kg/1 000 g})}$$

$$V_{\text{He}} = 1.68\times10^4\text{ cm}^3 = \boxed{16.8\text{ liters}}$$

(b) The rate at which energy is supplied to the rod in order to maintain constant temperatures is given by

$$\mathcal{P} = kA\left(\frac{dT}{dx}\right) = (31.0\text{ J/s cm K})(2.50\text{ cm}^2)\left(\frac{295.8\text{ K}}{25.0\text{ cm}}\right) = 917\text{ W}$$

This power supplied to the helium will produce a "boil-off" rate of

$$\frac{\mathcal{P}}{\rho L_v} = \frac{(917\text{ W})(10^3\text{ g/kg})}{(0.125\text{ g/cm}^3)(2.09\times10^4\text{ J/kg})} = 351\text{ cm}^3\text{/s} = \boxed{0.351\text{ L/s}}$$

**P17.61** $Q = mc\Delta T = (\rho V)c\Delta T$ so that when a constant temperature difference $\Delta T$ is maintained,

the rate of adding energy to the liquid is $\mathcal{P} = \frac{dQ}{dt} = \rho\left(\frac{dV}{dt}\right)c\Delta T = \rho Rc\Delta T$

and the specific heat of the liquid is $c = \boxed{\frac{\mathcal{P}}{\rho R\Delta T}}$

**P17.62** (a) Work done by the gas is the negative of the area under the *PV* curve

$$W=-P_i\left(\frac{V_i}{2}-V_i\right)=\boxed{+\frac{P_iV_i}{2}}$$

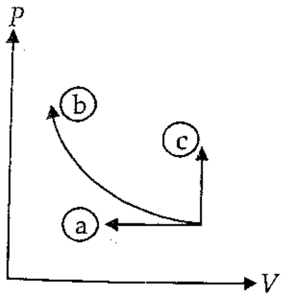

FIG. P17.62

(b) In this case the area under the curve is $W=-\int P\,dV$. Since the process is isothermal,

$$PV=P_iV_i=4P_i\left(\frac{V_i}{4}\right)=nRT_i$$

and $$W=-\int_{V_i}^{V_i/4}\left(\frac{dV}{V}\right)(P_iV_i)=-P_iV_i\ln\left(\frac{V_i/4}{V_i}\right)=P_iV_i\ln 4$$

$$=\boxed{+1.39P_iV_i}$$

(c) The area under the curve is 0 and $\boxed{W=0}$.

***P17.63** The initial moment of inertia of the disk is

$$\frac{1}{2}MR^2=\frac{1}{2}\rho VR^2=\frac{1}{2}\rho\pi R^2tR^2=\frac{1}{2}\left(8\,920\ \text{kg/m}^3\right)\pi(28\ \text{m})^4 1.2\ \text{m}=1.033\times10^{10}\ \text{kg}\cdot\text{m}^2$$

The rotation speeds up as the disk cools off, according to

$$I_i\omega_i=I_f\omega_f$$

$$\frac{1}{2}MR_i^2\omega_i=\frac{1}{2}MR_f^2\omega_f=\frac{1}{2}MR_i^2\left(1-\alpha|\Delta T|\right)^2\omega_f$$

$$\omega_f=\omega_i\frac{1}{\left(1-\alpha|\Delta T|\right)^2}=25\ \text{rad/s}\frac{1}{\left[1-\left(17\times10^{-6}\ 1/^\circ\text{C}\right)830^\circ\text{C}\right]^2}=25.720\,7\ \text{rad/s}$$

(a) The kinetic energy increases by

$$\frac{1}{2}I_f\omega_f^2-\frac{1}{2}I_i\omega_i^2=\frac{1}{2}I_i\omega_i\omega_f-\frac{1}{2}I_i\omega_i^2=\frac{1}{2}I_i\omega_i\left(\omega_f-\omega_i\right)$$

$$=\frac{1}{2}1.033\times10^{10}\ \text{kg}\cdot\text{m}^2(25\ \text{rad/s})0.720\,7\ \text{rad/s}=\boxed{9.31\times10^{10}\ \text{J}}$$

(b) $\Delta E_{\text{int}}=mc\Delta T=2.64\times10^7\ \text{kg}(387\ \text{J/kg}\cdot{}^\circ\text{C})(20^\circ\text{C}-850^\circ\text{C})=\boxed{-8.47\times10^{12}\ \text{J}}$

(c) As $8.47\times10^{12}$ J leaves the fund of internal energy, $9.31\times10^{10}$ J changes into extra kinetic energy, and the rest, $\boxed{8.38\times10^{12}\ \text{J}}$ is radiated.

***P17.64** The loss of mechanical energy is

$$\frac{1}{2}mv_i^2+\frac{GM_Em}{R_E}=\frac{1}{2}670\text{ kg}\left(1.4\times10^4\text{ m/s}\right)^2+\frac{6.67\times10^{-11}\text{ Nm}^2\;5.98\times10^{24}\text{ kg }670\text{ kg}}{\text{kg}^2\;6.37\times10^6\text{ m}}$$

$$=6.57\times10^{10}\text{ J}+4.20\times10^{10}\text{ J}=1.08\times10^{11}\text{ J}$$

One half becomes extra internal energy in the aluminum: $\Delta E_{\text{int}}=5.38\times10^{10}\text{ J}$. To raise the temperature of the aluminum to the melting point requires energy

$$mc\Delta T=670\text{ kg }900\frac{\text{J}}{\text{kg}^\circ\text{C}}\left(660-\left(-15^\circ\text{C}\right)\right)=4.07\times10^8\text{ J}.$$

To melt it, $mL=670\text{ kg }3.97\times10^5\text{ J/kg}=2.66\times10^8\text{ J}$. To raise it to the boiling point, $mc\Delta T=670(1\,170)(2\,450-660)\text{J}=1.40\times10^9\text{ J}$. To boil it, $mL=670\text{ kg }1.14\times10^7\text{ J/kg}=7.64\times10^9\text{ J}$. Then

$$5.38\times10^{10}\text{ J}=9.71\times10^9\text{ J}+670(1\,170)\left(T_f-2\,450^\circ\text{C}\right)\text{J/}^\circ\text{C}$$

$$T_f=\boxed{5.87\times10^4\,^\circ\text{C}}$$

**P17.65** The power incident on the solar collector is

$$\mathcal{P}_i=IA=\left(600\text{ W/m}^2\right)\left[\pi(0.300\text{ m})^2\right]=170\text{ W}.$$

For a 40.0% reflector, the collected power is $\mathcal{P}_c=67.9\text{ W}$. The total energy required to increase the temperature of the water to the boiling point and to evaporate it is $Q=cm\Delta T+mL_V$:

$$Q=0.500\text{ kg}\left[(4\,186\text{ J/kg }^\circ\text{C})(80.0^\circ\text{C})+2.26\times10^6\text{ J/kg}\right]=1.30\times10^6\text{ J}.$$

The time interval required is $\Delta t=\dfrac{Q}{\mathcal{P}_c}=\dfrac{1.30\times10^6\text{ J}}{67.9\text{ W}}=\boxed{5.31\text{ h}}$.

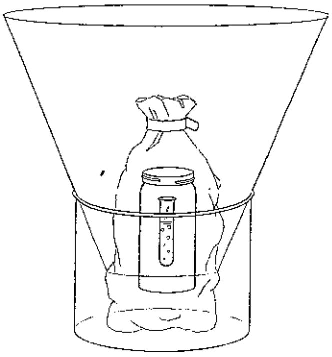

FIG. P17.65

**P17.66** (a) $Fv=(50.0\text{ N})(40.0\text{ m/s})=\boxed{2\,000\text{ W}}$

(b) Energy received by each object is $(1\,000\text{ W})(10\text{ s})=10^4\text{ J}=2\,389\text{ cal}$. The specific heat of iron is $0.107\text{ cal/g }^\circ\text{C}$, so the heat capacity of each object is $5.00\times10^3\times0.107=535.0\text{ cal/}^\circ\text{C}$.

$$\Delta T=\frac{2\,389\text{ cal}}{535.0\text{ cal/}^\circ\text{C}}=\boxed{4.47^\circ\text{C}}$$

**P17.67** (a) The block starts with $K_i = \frac{1}{2}mv_i^2 = \frac{1}{2}(1.60\text{ kg})(2.50\text{ m/s})^2 = 5.00\text{ J}$

All this becomes extra internal energy in ice, melting some according to $"Q" = m_{\text{ice}}L_f$. Thus, the mass of ice that melts is

$$m_{\text{ice}} = \frac{"Q"}{L_f} = \frac{K_i}{L_f} = \frac{5.00\text{ J}}{3.33\times10^5\text{ J/kg}} = 1.50\times10^{-5}\text{ kg} = \boxed{15.0\text{ mg}}.$$

For the block: $Q = 0$ (no energy flows by heat since there is no temperature difference)

$W = -5.00\text{ J}$

$\Delta E_{\text{int}} = 0$ (no temperature change)

and $\Delta K = -5.00\text{ J}$

For the ice, $Q = 0$

$W = +5.00\text{ J}$

$\Delta E_{\text{int}} = +5.00\text{ J}$

and $\Delta K = 0$

(b) Again, $K_i = 5.00\text{ J}$ and $m_{\text{ice}} = \boxed{15.0\text{ mg}}$

For the block of ice: $Q = 0$; $\Delta E_{\text{int}} = +5.00\text{ J}$; $\Delta K = -5.00\text{ J}$

so $W = 0$.

For the copper, nothing happens: $Q = \Delta E_{\text{int}} = \Delta K = W = 0$

(c) Again, $K_i = 5.00\text{ J}$ Both blocks must rise equally in temperature.

$"Q" = mc\Delta T$: $\Delta T = \frac{"Q"}{mc} = \frac{5.00\text{ J}}{2(1.60\text{ kg})(387\text{ J/kg °C})} = \boxed{4.04\times10^{-3}\,°\text{C}}$

At any instant, the two blocks are at the same temperature, so for both $Q = 0$.

For the moving block: $\Delta K = -5.00\text{ J}$

and $\Delta E_{\text{int}} = +2.50\text{ J}$

so $W = -2.50\text{ J}$

For the stationary block: $\Delta K = 0$

and $\Delta E_{\text{int}} = +2.50\text{ J}$

so $W = +2.50\text{ J}$

For each object in each situation, the general continuity equation for energy, in the form $\Delta K + \Delta E_{\text{int}} = W + Q$, correctly describes the relationship between energy transfers and changes in the object's energy content.

**P17.68**

$$\frac{L\rho A\,dx}{dt}=kA\left(\frac{\Delta T}{x}\right)$$

$$L\rho\int_{4.00}^{8.00}x\,dx=k\Delta T\int_{0}^{\Delta t}dt$$

$$L\rho\left.\frac{x^2}{2}\right|_{4.00}^{8.00}=k\Delta T\Delta t$$

$$\left(3.33\times10^{5}\ \text{J/kg}\right)\left(917\ \text{kg/m}^3\right)\left(\frac{(0.080\,0\ \text{m})^2-(0.040\,0\ \text{m})^2}{2}\right)=(2.00\ \text{W/m}\cdot{}^\circ\text{C})(10.0^\circ\text{C})\Delta t$$

$$\Delta t=3.66\times10^{4}\ \text{s}=\boxed{10.2\ \text{h}}$$

**P17.69**

$$A=A_{\text{end walls}}+A_{\text{ends of attic}}+A_{\text{side walls}}+A_{\text{roof}}$$

$$A=2(8.00\ \text{m}\times5.00\ \text{m})+2\left[2\times\frac{1}{2}\times4.00\ \text{m}\times(4.00\ \text{m})\tan37.0^\circ\right]$$

$$+2(10.0\ \text{m}\times5.00\ \text{m})+2(10.0\ \text{m})\left(\frac{4.00\ \text{m}}{\cos37.0^\circ}\right)$$

$$A=304\ \text{m}^2$$

$$\mathcal{P}=\frac{kA\Delta T}{L}=\frac{\left(4.80\times10^{-4}\ \text{kW/m}\cdot{}^\circ\text{C}\right)\left(304\ \text{m}^2\right)(25.0^\circ\text{C})}{0.210\ \text{m}}=17.4\ \text{kW}=4.15\ \text{kcal/s}$$

Thus, the energy lost per day by heat is $(4.15\ \text{kcal/s})(86\,400\ \text{s})=3.59\times10^{5}\ \text{kcal/day}$.

The gas needed to replace this loss is $\dfrac{3.59\times10^{5}\ \text{kcal/day}}{9\,300\ \text{kcal/m}^3}=\boxed{38.6\ \text{m}^3/\text{day}}$

**P17.70**

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

or

$$Q_{\text{Al}}=-(Q_{\text{water}}+Q_{\text{calo}})$$

$$m_{\text{Al}}c_{\text{Al}}\left(T_f-T_i\right)_{\text{Al}}=-\left(m_wc_w+m_cc_c\right)\left(T_f-T_i\right)_w$$

$$(0.200\ \text{kg})c_{\text{Al}}(+39.3^\circ\text{C})=-\left[0.400\ \text{kg}(4186\ \text{J/kg}\cdot{}^\circ\text{C})+0.040\,0\ \text{kg}(630\ \text{J/kg}\cdot{}^\circ\text{C})\right](-3.70^\circ\text{C})$$

$$c_{\text{Al}}=\frac{6.29\times10^{3}\ \text{J}}{7.86\ \text{kg}\cdot{}^\circ\text{C}}=\boxed{800\ \text{J/kg}\cdot{}^\circ\text{C}}$$

**P17.71** (a) $P_f=\boxed{100\ \text{kPa}}$, $T_f=\boxed{400\ \text{K}}$

$$V_f=\frac{nRT_f}{P_f}=\frac{2.00\ \text{mol}(8.314\ \text{J/mol}\cdot\text{K})(400\ \text{K})}{100\times10^{3}\ \text{Pa}}=0.0665\ \text{m}^3=\boxed{66.5\ \text{L}}$$

$$\Delta E_{\text{int}}=(3.50)nR\Delta T=3.50(2.00\ \text{mol})(8.314\ \text{J/mol}\cdot\text{K})(100\ \text{K})=\boxed{5.82\ \text{kJ}}$$

$$W=-P\Delta V=-nR\Delta T=-(2.00\ \text{mol})(8.314\ \text{J/mol}\cdot\text{K})(100\ \text{K})=\boxed{-1.66\ \text{kJ}}$$

$$Q=\Delta E_{\text{int}}-W=5.82\ \text{kJ}+1.66\ \text{kJ}=\boxed{7.84\ \text{kJ}}$$

*continued on next page*

(b) $T_f = \boxed{400\text{ K}}$, $V_f = V_i = \frac{nRT_i}{P_i} = \frac{2.00\text{ mol}(8.314\text{ J/mol}\cdot\text{K})(300\text{ K})}{100\times 10^3\text{ Pa}} = 0.0499\text{ m}^3 = \boxed{49.9\text{ L}}$

$P_f = P_i\left(\frac{T_f}{T_i}\right) = 100\text{ kPa}\left(\frac{400\text{ K}}{300\text{ K}}\right) = \boxed{133\text{ kPa}}$, $W = -\int PdV = \boxed{0}$ since $V = \text{constant}$

$\Delta E_{\text{int}} = \boxed{5.82\text{ kJ}}$ as in part (a) $Q = \Delta E_{\text{int}} - W = 5.82\text{ kJ} - 0 = \boxed{5.82\text{ kJ}}$

(c) $P_f = \boxed{120\text{ kPa}}$, $T_f = \boxed{300\text{ K}}$, $V_f = V_i\left(\frac{P_i}{P_f}\right) = 49.9\text{ L}\left(\frac{100\text{ kPa}}{120\text{ kPa}}\right) = \boxed{41.6\text{ L}}$,

$\Delta E_{\text{int}} = (3.50)nR\Delta T = \boxed{0}$ since $T = \text{constant}$

$W = -\int PdV = -nRT_i\int_{V_i}^{V_f}\frac{dV}{V} = -nRT_i\ln\left(\frac{V_f}{V_i}\right) = -nRT_i\ln\left(\frac{P_i}{P_f}\right)$

$W = -(2.00\text{ mol})(8.314\text{ J/mol K})(300\text{ K})\ln\left(\frac{100\text{ kPa}}{120\text{ kPa}}\right) = \boxed{+909\text{ J}}$

$Q = \Delta E_{\text{int}} - W = 0 - 909\text{ J} = \boxed{-909\text{ J}}$

(d) $P_f = \boxed{120\text{ kPa}}$, $\gamma = \frac{C_P}{C_V} = \frac{C_V + R}{C_V} = \frac{3.50R + R}{3.50R} = \frac{4.50}{3.50} = \frac{9}{7}$

$P_fV_f^{\gamma} = P_iV_i^{\gamma}$: so $V_f = V_i\left(\frac{P_i}{P_f}\right)^{1/\gamma} = 49.9\text{ L}\left(\frac{100\text{ kPa}}{120\text{ kPa}}\right)^{7/9} = \boxed{43.3\text{ L}}$

$T_f = T_i\left(\frac{P_fV_f}{P_iV_i}\right) = 300\text{ K}\left(\frac{120\text{ kPa}}{100\text{ kPa}}\right)\left(\frac{43.3\text{ L}}{49.9\text{ L}}\right) = \boxed{312\text{ K}}$

$\Delta E_{\text{int}} = (3.50)nR\Delta T = 3.50(2.00\text{ mol})(8.314\text{ J/mol}\cdot\text{K})(12.4\text{ K}) = \boxed{722\text{ J}}$

$Q = \boxed{0}$ (adiabatic process)

$W = -Q + \Delta E_{\text{int}} = 0 + 722\text{ J} = \boxed{+722\text{ J}}$

***P17.72** (a) $PV^{\gamma} = k$. So, $W = -\int_i^f PdV = -k\int_i^f\frac{dV}{V^{\gamma}} = \frac{P_fV_f - P_iV_i}{\gamma - 1}$

(b) $dE_{\text{int}} = dQ + dW$ and $dQ = 0$ for an adiabatic process.

Therefore, $W = +\Delta E_{\text{int}} = nC_V\left(T_f - T_i\right)$

To show consistency between these two equations, consider that $\gamma = \frac{C_p}{C_V}$ and $C_p - C_V = R$

Therefore, $\frac{1}{\gamma - 1} = \frac{C_V}{R}$

Using this, result found on part (a) becomes

$$W = \left(P_fV_f - P_iV_i\right)\frac{C_V}{R}$$

Also, for an ideal gas $\frac{PV}{R} = nT$ so that $W = nC_V\left(T_f - T_i\right)$

***P17.73** (a) $W = nC_V\left(T_f - T_i\right)$

$$-2\,500\text{ J} = 1\text{ mol}\frac{3}{2}8.314\text{ J/mol}\cdot\text{K}\left(T_f - 500\text{ K}\right)$$

$$T_f = \boxed{300\text{ K}}$$

(b) $P_iV_i^{\gamma} = P_fV_f^{\gamma}$

$$P_i\left(\frac{nRT_i}{P_i}\right)^{\gamma} = P_f\left(\frac{nRT_f}{P_f}\right)^{\gamma} \qquad T_i^{\gamma}P_i^{1-\gamma} = T_f^{\gamma}P_f^{1-\gamma}$$

$$\frac{T_i^{\gamma/(\gamma-1)}}{P_i} = \frac{T_f^{\gamma/(\gamma-1)}}{P_f} \qquad P_f = P_i\left(\frac{T_f}{T_i}\right)^{\gamma/(\gamma-1)}$$

$$P_f = P_i\left(\frac{T_f}{T_i}\right)^{(5/3)(3/2)} = 3.60\text{ atm}\left(\frac{300}{500}\right)^{5/2} = \boxed{1.00\text{ atm}}$$

**P17.74** The ball loses energy $\frac{1}{2}mv_i^2 - \frac{1}{2}mv_f^2 = \frac{1}{2}(0.142\text{ kg})\left[(47.2)^2 - (42.5)^2\right]\text{ m}^2/\text{s}^2 = 29.9\text{ J}$

The air volume is $V = \pi(0.037\,0\text{ m})^2(19.4\text{ m}) = 0.083\,4\text{ m}^3$

and its quantity is $n = \frac{PV}{RT} = \frac{1.013\times10^5\text{ Pa}\left(0.083\,4\text{ m}^3\right)}{(8.314\text{ J/mol}\cdot\text{K})(293\text{ K})} = 3.47\text{ mol}$.

The air absorbs energy according to $Q = nC_P\Delta T$. So

$$\Delta T = \frac{Q}{nC_P} = \frac{29.9\text{ J}}{3.47\text{ mol}\,\frac{7}{2}(8.314\text{ J/mol}\cdot\text{K})} = \boxed{0.296^\circ\text{C}}$$

**P17.75** (a) $n = \frac{PV}{RT} = \frac{\left(1.013\times10^5\text{ Pa}\right)\left(5.00\times10^{-3}\text{ m}^3\right)}{(8.314\text{ J/mol}\cdot\text{K})(300\text{ K})} = \boxed{0.203\text{ mol}}$

(b) $T_B = T_A\left(\frac{P_B}{P_A}\right) = 300\text{ K}\left(\frac{3.00}{1.00}\right) = \boxed{900\text{ K}}$

$$T_C = T_B = \boxed{900\text{ K}}$$

$$V_C = V_A\left(\frac{T_C}{T_A}\right) = 5.00\text{ L}\left(\frac{900}{300}\right) = \boxed{15.0\text{ L}}$$

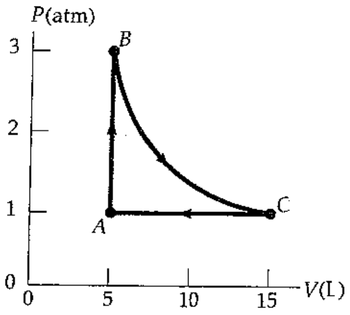

FIG. P17.75

(c) $E_{\text{int},A} = \frac{3}{2}nRT_A = \frac{3}{2}(0.203\text{ mol})(8.314\text{ J/mol}\cdot\text{K})(300\text{ K})$

$$= \boxed{760\text{ J}}$$

$$E_{\text{int},B} = E_{\text{int},C} = \frac{3}{2}nRT_B = \frac{3}{2}(0.203\text{ mol})(8.314\text{ J/mol}\cdot\text{K})(900\text{ K}) = \boxed{2.28\text{ kJ}}$$

*continued on next page*

(d)

| | P (atm) | V(L) | T(K) | $E_{\text{int}}$ (kJ) |
|---|---|---|---|---|
| A | 1.00 | 5.00 | 300 | 0.760 |
| B | 3.00 | 5.00 | 900 | 2.28 |
| C | 1.00 | 15.00 | 900 | 2.28 |

(e) For the process *AB*, lock the piston in place and put the cylinder into an oven at 900 K. For *BC*, keep the sample in the oven while gradually letting the gas expand to lift a gradually decreasing load on the piston as far as it can. For *CA*, carry the cylinder back into the room at 300 K and let the gas cool without touching the piston yourself.

(f) For *AB*: $W=\boxed{0}$, $\Delta E_{\text{int}}=E_{\text{int},B}-E_{\text{int},A}=(2.28-0.760)\text{ kJ}=\boxed{1.52\text{ kJ}}$

$Q=\Delta E_{\text{int}}-W=\boxed{1.52\text{ kJ}}$

For *BC*: $\Delta E_{\text{int}}=\boxed{0}$, $W=-nRT_B\ln\left(\dfrac{V_C}{V_B}\right)$

$W=-(0.203\text{ mol})(8.314\text{ J/mol}\cdot\text{K})(900\text{ K})\ln(3.00)=\boxed{-1.67\text{ kJ}}$

$Q=\Delta E_{\text{int}}-W=\boxed{1.67\text{ kJ}}$

For *CA*: $\Delta E_{\text{int}}=E_{\text{int},A}-E_{\text{int},C}=(0.760-2.28)\text{ kJ}=\boxed{-1.52\text{ kJ}}$

$W=-P\Delta V=-nR\Delta T=-(0.203\text{ mol})(8.314\text{ J/mol}\cdot\text{K})(-600\text{ K})=\boxed{1.01\text{ kJ}}$

$Q=\Delta E_{\text{int}}-W=-1.52\text{ kJ}-1.01\text{ kJ}=\boxed{-2.53\text{ kJ}}$

(g) We add the amounts of energy for each process to find them for the whole cycle.

$$Q_{ABCA}=+1.52\text{ kJ}+1.67\text{ kJ}-2.53\text{ kJ}=\boxed{0.656\text{ kJ}}$$

$$W_{ABCA}=0-1.67\text{ kJ}+1.01\text{ kJ}=\boxed{-0.656\text{ kJ}}$$

$$(\Delta E_{\text{int}})_{ABCA}=+1.52\text{ kJ}+0-1.52\text{ kJ}=\boxed{0}$$

***P17.76** (a) The chemical energy input becomes partly work output and partly internal energy. The energy flow each second is described by

$$400\text{ kcal/h}=60\text{ J/s}+\frac{mL}{\Delta t}=400\text{ kcal/h}\left(\frac{4\,186\text{ J}}{1\text{ kcal}}\right)\left(\frac{1\text{ h}}{3\,600\text{ s}}\right)=465\text{ W}$$

$$\frac{m}{\Delta t}L=465\text{ W}-60\text{ W}=405\text{ J/s}$$

$$\frac{m}{\Delta t}=\frac{405\text{ J/s}}{2.26\times10^{6}\text{ J/kg}}\left(\frac{3\,600\text{ s}}{1\text{ h}}\right)=\boxed{0.645\text{ kg/h}}$$

(b) The rate of fat burning is ideally $\dfrac{400\text{ kcal/h}}{9\text{ kcal/g}}=0.044\,4\text{ kg/h}$. The $0.044\,4\text{ kg/h}$ of water produced by metabolism is this fraction of the water needed for cooling: $\dfrac{0.0\,444\text{ kg/h}}{0.645\text{ kg/h}}=\boxed{0.068\,9}=6.89\%$. Moral: drink plenty of fruit juice while you exercise.