CHAPTER 14

HEAT

OBJECTIVES

After studying the material of this chapter, the student should be able to:

- convert from joules to calories and kilocalories and vice versa.
- distinguish between the concepts of temperature and heat.
- explain what is meant by specific heat, latent heat of fusion, and latent heat of vaporization.
- apply the law of conservation of energy to problems involving calorimetry.
- distinguish the three ways that heat transfer occurs: conduction, convection, and radiation.
- solve problems involving the rate of heat transfer by convection and radiation.

KEY TERMS AND PHRASES

SI unit of heat is the joule (J). Also used are units related to the joule, namely, the **calorie** and **kilocalorie** where 4.184 J = 1 calorie (exactly) and 1000 cal = 1 kilocalorie.

internal energy consists of the total potential and kinetic energy of all of the atoms in the substance.

heat is the transfer of energy (usually thermal energy) from an object at higher temperature to one at a lower temperature.

specific heat is the amount of heat required to raise the temperature of 1 kg of a substance by 1°C. For water at 15°C, the specific heat is 1.00 kcal/kg°C or 4180 J/kg°C.

calorimetry is the quantitative measurement of the heat exchanged between two substances that are initially at different temperatures. Calorimetry is based on the law of conservation of energy and assumes that the heat lost by an object(s) at the higher temperature equals the heat gained by the object(s) at the lower temperature, i.e., heat lost + heat gained = 0.

change of phase refers to an object changing from the solid state to the liquid state and vice versa or from the liquid state to the gaseous state and vice versa.

latent heat of fusion refers to the energy that must be added or removed from a substance in order for the substance to change from the solid state to the liquid state or vice versa. The change occurs at the melting (freezing) point of the substance and no change of temperature occurs during the change of phase.

latent heat of vaporization refers to the energy that must be added or removed from a substance in order for the substance to change from the liquid state to the gaseous state or vice versa. The change occurs at the boiling (condensation) point of the substance and no change of temperature occurs during the change of phase.

conduction of heat is the result of collisions between molecules in a material. In a solid, the molecules are not free to move throughout the volume of the solid. The increase in kinetic energy of the molecules is in the form of vibrational kinetic energy.

convection is transfer of heat due to mass movement of warm material from one region to another. In the process of moving, the warm material displaces cold material.

radiation is the transfer of energy due to electromagnetic waves. Electromagnetic waves require no substance to transfer the energy.

thermal equilibrium between an object and its surroundings is reached when they reach the same temperature, i.e., $T_{1f} = T_{2f}$.

SUMMARY OF MATHEMATICAL FORMULAS

internal energy of an ideal gas	$U = 3/2\ n\ R\ T$	The internal energy (U) of an ideal gas depends on the number of moles (n) and the temperature in degrees Kelvin (T). R represents the universal gas constant.
heat transfer and specific heat	$Q = m\ c\ \Delta T$	The heat (Q) required to raise the temperature of a substance is related to the mass (m), specific heat (c) of the substance, and the change in temperature (ΔT).
latent heat of fusion or latent heat of vaporization	$Q = m\ \ell$	The heat (Q) added (or removed) in order to cause a substance to undergo a change of phase depends on the object's mass (m) and the latent heat (ℓ), where ℓ is either the heat of fusion (ℓ_F) or heat of vaporization (ℓ_V).
thermal conduction	$\Delta Q/\Delta t = k\ A\ (T_1 - T_2)/\ell$	The rate of heat flow ($\Delta Q/\Delta t$) through a substance due to conduction is related to the cross-sectional area of the object (A), the object's thickness (ℓ), and the temperature difference between the ends of the object ($T_1 - T_2$) in °C. k is the thermal conductivity of the material.

Stefan-Boltzmann's equation	$\Delta Q/\Delta t = e\ \sigma\ A\ T^4$	The rate at which an object radiates electromagnetic energy ($\Delta Q/\Delta t$) is related to the object's surface area(A), the object's temperature (T) in degrees Kelvin, and the emissivity (e) of the material. Stefan-Boltzmann's constant σ = 5.67 x 10^{-8} J/(s m^2 K^4).
net rate of radiant energy transferred	$\Delta Q/\Delta t = e\ \sigma\ A\ (T_1^4 - T_2^4)$	The net rate of radiant energy flow be tween an object and its surroundings is related to the surface area, emissivity and the difference in the temperatures between the object (T_1) and its surroundings (T_2).

CONCEPTS AND EQUATIONS

Units of Heat

The **SI** unit of heat is the joule (J). Also used are units related to the joule, namely, the **calorie** and **kilocalorie** where 4.184 J = 1 calorie (exactly) and 1000 cal = 1 kilocalorie. The kilocalorie is also known as the "large" calorie and is the unit associated with the energy content of foods.

Temperature, Heat, and Internal Energy

Temperature is the measure of the average kinetic energy of the individual molecules in a substance. All objects, whether solid, liquid, or gas, consist of atoms that are in motion. The **internal energy** consists of the total potential and kinetic energy of all of the atoms in the substance.

In an ideal monatomic gas we do not consider attractive or repulsive forces between atoms and so the internal energy (U) would be the total number of molecules in a gas times the average kinetic energy of the molecules.

$$U = N\ \overline{KE}$$

$$U = N\ (\tfrac{1}{2}\ m\ \overline{v^2}) = (3/2\ k\ T) = 3/2\ n\ R\ T$$

Heat is the transfer of energy (usually thermal energy) from an object at higher temperature to one at a lower temperature.

Specific Heat

The amount of heat (Q) required to raise the temperature of a substance depends on the quantity of matter or mass (m), the **specific heat** (c) of the substance involved and the change in temperature (ΔT). This is expressed mathematically as

$$Q = m\ c\ \Delta T$$

c is the specific heat of the substance. This is the amount of heat required to raise the temperature of 1 kg of a substance by 1°C. For water at 15°C, c = 1.00 kcal/kg°C = 4180 J/kg°C.

Calorimetry

Calorimetry is the quantitative measurement of the heat exchanged between two substances that are initially at different temperatures. For example, if hot water is added to a container of cold water, some of the heat energy of the hot water will be transferred to the cold water and also to the container. In calorimetry, this heat exchange is treated quantitatively.

Calorimetry is based on the law of conservation of energy and assumes that the heat lost by an object(s) at the higher temperature equals the heat gained by the object(s) at the lower temperature, i.e., heat lost + heat gained = 0 or heat gained = - heat lost.

EXAMPLE PROBLEM 1. A 0.0100 kg lead bullet moving at 100 m/s imbeds itself in a large block of wood. All of the kinetic energy lost by the lead bullet is transferred into heat which is shared equally by the bullet and the block of wood. Determine the temperature change of the bullet. The specific heat of lead is 0.0310 kcal/kg°C.

Part a. Step 1. Determine the amount of mechanical energy dissipated in the form of heat.	Solution: (Section 14-4) $Q = -\Delta KE = -(KE_f - KE_i)$ $= -(\frac{1}{2} m v_f^2 - \frac{1}{2} m v_i^2)$ $= -[\frac{1}{2}(0.0100 \text{ kg})(0 \text{ m/s})^2 - \frac{1}{2}(0.0100 \text{ kg})(100 \text{ m/s})^2]$ $Q = 50.0 \text{ J}$
Part a. Step 2. Determine the change in temperature of the bullet.	The heat transferred to the bullet $Q = \frac{1}{2}(50.0 \text{ J}) = 25.0 \text{ J}$ $Q = m\, c\, \Delta T$ $(25.0 \text{ J})(1.0 \text{ kcal}/4180 \text{ J}) = (0.0100 \text{ kg})(0.0310 \text{ kcal/kg °C})\, \Delta T$ $\Delta T = 19.3 \text{ C}^\circ$

Latent Heat

Latent Heat is the energy that must be added or removed from a substance in order for a **change of phase** to occur. For changes from the solid to the liquid state or vice versa the heat energy required is the **latent heat of fusion**. For changes from the liquid state to the gas state and vice versa the heat energy is the **latent heat of vaporization.**

Heat added to ice at 0°C causes ice to melt and a change of phase from the solid state to the liquid state occurs. There is no change in temperature during the phase change. The heat added overcomes the potential energy associated with the attractive forces between the molecules in the solid (ice). There is no increase in kinetic energy of the molecules until all of the ice melts and there is no increase in temperature during the phase change.

The reverse process occurs when water returns to the solid phase from the liquid phase. Heat must be removed from the system even though there is no change of temperature.

Table 14-3 in the textbook lists the latent heats of fusion and vaporization for a number of substances. For water, the heat of fusion is 79.7 kcal/kg or 333 kJ/kg and the heat of vaporization is 539 kcal/kg or 2260 kJ/kg. The heat required for a phase change is given by

$Q = m\,\ell$ where ℓ is the heat of fusion (ℓ_F) or heat of vaporization (ℓ_V).

TEXTBOOK QUESTION 6. Why does water in a canteen stay cooler if the cloth jacket surrounding the canteen is kept moist?

ANSWER: Latent heat is the energy that must be added or removed from a substance in order for a change of phase to occur. For changes from the liquid state to the gas state and vice versa the heat energy is the latent heat of vaporization.

Energy is required to cause water to evaporate from the cloth jacket. As the water evaporates, it removes energy from the metal container which makes up the shell of the canteen. As a result, the water in the canteen remains cooler than it would if the cloth jacket were not kept moist.

TEXTBOOK QUESTION 7. Explain why burns caused by steam on the skin are often more severe than burns caused by water at 100°C.

ANSWER: The heat of vaporization of water is 539 Kcal/kg and this heat is released when the steam strikes the skin and condenses into water.

If the heat present in 1 gram of steam as it condenses into water at 100°C is completely absorbed by the skin, the skin absorbs 539 cal of heat. If this same 1 gram of water now cools from 100°C to 37°C (body temperature), it releases only 73 cal of heat. The burns caused by steam at 100°C are more severe than an equal mass of water at 100°C.

TEXTBOOK QUESTION 9. Will potatoes cook faster if the water is boiling faster?

ANSWER: Under 1 atmosphere of pressure, water boils at approximately 100°C whether the water is boiling fast or slow. The time required for the potatoes to cook will be the same but energy will be saved if the water is set for a slow boil.

EXAMPLE PROBLEM 2. A 1.00 kg aluminum pot holds 2.00 kg of water at 20.0°C. Determine the amount of steam which must be added at 100°C to raise the temperature of the water and pot to 25.0°C. Note: the heat of vaporization of steam is 540 kcal/kg, while the specific heat of water is 1.00 kcal/kg °C, and the specific heat of aluminum is 0.220 kcal/kg °C.

Part a. Step 1. Determine the a temperature change for each substance in the system.	Solution: (Sections 14-4 and 14-5) Steam at 100°C to water at 100°C: no temperature change occurs during the change of phase to hot water. Hot water at 100°C to water at 25.0°C: ΔT_{hw} = 25.0°C - 100°C = -75.0 C° Aluminum pot: ΔT_{Al} = 25.0°C - 20.0°C = 5.00 C° Cold water at 20.0°C to water at 25.0°C: ΔT_{cw} = 25.0°C - 20.0°C = 5.00 C°
Part a. Step 2. Derive a formula for the heat lost by the steam and the hot water.	The steam becomes hot water which then loses heat until its temperature reaches 25.0°C. Therefore, the mass of the steam equals the mass of the hot water, i.e. $m_{hw} = m_{steam}$ heat lost by steam + hot water = $Q_{steam} + Q_{hw}$ $Q_{steam} + Q_{hw} = m_{steam}\,\ell_v + m_{hw}\,c_w\,\Delta T_{hw}$ $= m_{steam}$ (-540 kcal/kg) + m_{hw}(1.0 kcal/kg°C)(-75.0°C) but $m_{steam} = m_{hw}$ $Q_{steam} + Q_{hw}$ = -[540 kcal/kg + 75.0 kcal/kg] m_{steam} heat lost = -(615 kcal/kg) m_{steam}
Part a. Step 3. Determine the heat gained by the pot and cold water.	Note: let the mass of the cold water be m_{cw}. heat gained by pot + cold water = $m_{Al}\,c_{Al}\;\Delta T_{Al} + m_{cw}\,c_w\;\Delta T_{cw}$ $heat_{gained}$ = [(1.00 kg)(0.220 kcal/kg°C)+ (2.0 kg)(1.0 kcal/kg°C)](5.00°C) $heat_{gained}$ = 11.1 kcal
Part a. Step 4. Apply the law of conservation of energy and solve for the mass of the steam.	The heat gained by the aluminum and cold water plus the heat lost by the steam and the hot water must equal zero. heat gained + heat lost = 0 11.1 kcal + -(615 kcal/kg)m_{steam} = 0 m_{steam} = (- 11.1 kcal)/(-615 kcal/kg) = 0.0180 kg or 18.0 grams

Heat Transfer: Conduction, Convection, and Radiation

There are three ways to transfer heat from one object or place to another. In a particular situation, one or more of the processes may be involved in the heat transfer.

Conduction

Conduction of heat is the result of collisions between molecules in a material. In a solid, the molecules are not free to move throughout the volume of the solid. The increase in kinetic energy of the molecules is in the form of vibrational kinetic energy.

If one end of the solid, e.g., a metal rod, is held in a flame, the molecules in that end will have a higher average vibrational kinetic energy than molecules further along the rod. The higher energy molecules transfer some of this energy to adjacent molecules via molecular collisions. As a result, heat energy is gradually transferred through the object.

The rate of heat flow through a substance due to conduction is given by the equation

$$\Delta Q/\Delta t = K\ A\ (T_1 - T_2)/\ell$$

$\Delta Q/\Delta t$ is the heat transferred per unit time, A is the cross-sectional area of the object, and ℓ is the object's thickness. $T_1 - T_2$ is the temperature difference between the ends of the object in °C, where T_1 is greater than T_2. K is the **thermal conductivity** of the material and the unit of K is kcal/(s m °C).

EXAMPLE PROBLEM 3. 400 ml of hot coffee at 60.0°C is placed in a closed styrofoam cup which is 1.50 mm thick and surface area 850 cm^2. The day is windy and the air outside the cup remains at a constant temperature of 20.0°C. The thermal conductivity of styrofoam is 5.5×10^{-6} kcal/s m°C. Determine a) the initial rate of heat flow through the styrofoam, and b) the time required for the temperature of the coffee to cool from 60.0°C to 50.0°C. Assume that 400 ml of coffee has a mass of 0.400 kg and that specific heat of coffee is the same as that of water.

Part a. Step 1. Complete a data table and apply the equation for the conduction of heat through a substance.	Solution: (Section 14-6) $\ell = (1.50\ mm)(1\ m/1000\ mm) = 1.50 \times 10^{-3}\ m = 0.00150\ m$ $A = (850\ cm^2)(1\ m^2/10^4\ cm^2) = 8.50 \times 10^{-2}\ m^2 = 0.0850\ m^2$ $T_1 - T_2 = 60.0°C - 20.0°C = 40.0\ C°$ $\Delta Q/\Delta t = k\ A\ (T_1 - T_2)/\ell$ $= (5.5 \times 10^{-6}\ kcal/s\ m°C)(0.0850\ m^2)(40.0\ C°)/(0.00150\ m)$ $\Delta Q/\Delta t = 1.25 \times 10^{-3}\ kcal/s$

Part b. Step 1.

Determine the time required for the temperature of the coffee to cool from 60.0°C to 50.0°C.

The time for the temperature of the coffee to change from 60.0°C to 50.0°C may be determined as follows:

heat loss = $(\Delta Q/\Delta t)$(time interval)

but heat loss = $Q = m\ c\ \Delta T$

$(\Delta Q/\Delta t)$(time interval) = $m\ c\ \Delta T$

$(1.25 \times 10^{-3}\ \text{kcal/s})\ t = -(0.400\ \text{kg})(1.0\ \text{kcal/kg°C})(50.0°\text{C} - 60.0°\text{C})$

$t = 3200$ s or 53.3 minutes

Note: the answer is unrealistic due to a number of assumptions that would affect the time interval. For example, we have assumed that the cup is tightly sealed so that convective heat losses are negligible, rate of heat loss is constant, and the thickness of the cup is uniform. However, even with these assumptions we can see the advantage of using styrofoam cups for holding hot or cold liquids.

Convection

Convection is transfer of heat due to mass movement of warm material from one region to another. In the process of moving, the warm material displaces cold material. An example of this is a convection current present in a pan of water heated on a stove. The hot water rises from the bottom of the pan to the top while the cold water on the top sinks to the bottom. As the cold water sinks it is heated and the convection process continues until the boiling point is reached.

Radiation

Radiation is the transfer of energy due to electromagnetic waves. Electromagnetic waves, e.g. light from the sun, travel at the speed of light. They require no material medium to transport the waves, so light from very distant objects, e.g. the stars, is able to travel through the vacuum of outer space to the Earth. The rate at which an object radiates electromagnetic energy is given by the Stefan-Boltzmann's equation $\Delta Q/\Delta t = e\ \sigma\ A\ T^4$.

$\Delta Q/\Delta t$ is the rate at which energy leaves the object, A is the object's surface area, and T is the object's temperature in K. e is the **emissivity** of the material and is a characteristic property of the material. A perfect absorber is also a perfect emitter and has an emissivity value of 1. A perfect absorber is known as a perfect black body. A perfect reflector has an emissivity value of 0. $\sigma = 5.67 \times 10^{-8}\ \text{J/(s m}^2\ \text{K}^4)$ and is known as the Stefan-Boltzmann constant. The net rate of radiant energy flow between an object and its surroundings is given by

$$\Delta Q/\Delta t = e\ \sigma\ A\ (T_1^4 - T_2^4)$$

T_1 and T_2 are the temperatures in degrees Kelvin of the object and its surroundings.

Thermal equilibrium $(\Delta Q/\Delta t = 0)$ between an object and its surroundings is reached when they reach the same temperature, i.e., $T_1 = T_2$.

TEXTBOOK QUESTION 24. Why is the liner of a thermos bottle silvered (Fig. 14-15) and why does it have a vacuum between its two walls?

ANSWER: Silver reflects heat back into the liquid in the bottle and therefore heat loss due to radiation is kept to a minimum. The partial vacuum between the liner and the outer wall keeps heat loss due to convection to a minimum. The cork or styrofoam cap is a poor conductor of heat and if the seal is tight the rate of heat loss due to conduction is very low. Thus, the hot liquid in the thermos will be kept hot for several hours.

Note: the same arguments can be used to explain why cold liquids will remain cold for extended periods in a thermos.

EXAMPLE PROBLEM 4. A solid cylindrical metal bar is 2.00 cm in radius and is 20.0 cm long. The bar is heated until its temperature reaches 500°C. After it is removed from the source of heat it is placed in a room where the temperature is 20.0°C. Calculate the rate at which the bar radiates energy when it is first removed from the source of heat. Note: the emissivity value of the metal is 0.400.

Part a. Step 1. Calculate the temperature in degrees Kelvin.	Solution: (Section 14-8) 273°C + 500°C = 773 K 273°C + 20.0°C = 293 K
Part a. Step 2. Determine the surface area of the bar.	The lateral surface area of the bar = $2\pi rL$ while the area of each end = πr^2, therefore $A = 2\pi\ r\ L + \pi r^2 + \pi r^2$ $A = 2\pi(2.00\text{ cm})(20.0\text{ cm}) + \pi(2.00\text{ cm})^2 + \pi(2.00\text{ cm})^2 = 276\text{ cm}^2$ $A = (276\text{ cm}^2)(1.0\text{ m}/100\text{ cm})^2 = 2.76 \times 10^{-2}\text{ m}^2$
Part a. Step 3. Determine the rate at which energy is radiated.	$\Delta Q/\Delta t = e\ \sigma\ A\ T^4$ $\Delta Q/\Delta t = (0.400)(5.67 \times 10^{-8}\text{ J/s m}^2\text{ K}^4)(2.76 \times 10^{-2}\text{ m}^2)[(773\text{ K})^4 - (293\text{ K})^4]$ $\Delta Q/\Delta t = 220\text{ J/s} = 220\text{ watts}$

PROBLEM SOLVING SKILLS

For problems involving calorimetry:

1. Complete a data table for information both given and implied in the problem. This information should list the initial and final temperature of each substance, the specific heat of each substance, and the mass of each substance. If a phase change occurs, the list should include the latent heat of fusion or vaporization of the substance involved in the phase change.

2. Apply the law of conservation of energy and solve the problem. Remember that the sum of the heat gain and loss equals zero.

For problems involving heat transfer by conduction:

1. Complete a data table listing information both given and implied as well as the unknown quantity. This information should include the temperature on either side of the material, the thickness of the material, the cross-sectional area through which the heat transfer occurs, and the thermal conductivity of the substance. Also, the heat transferred and the time required for the transfer to occur should be included in the list.
2. Apply the formula for the rate of heat transfer through a material and solve for the unknown quantity.

For problems involving heat transfer by radiation:

1. Complete a data table listing information both given and implied. This list should include the temperature of the object and its surroundings, the surface area of the object, the object's emissivity and the Stefan-Boltzmann constant. Also, the heat transferred and the time required for the transfer should be included in the list.
2. Apply the formula for rate of heat transfer by radiation and solve for the unknown quantity.

SOLUTIONS TO SELECTED TEXTBOOK PROBLEMS

TEXTBOOK PROBLEM 3. An average active person consumes about 2500 Cal a day. (a) What is this in joules? (b) What is this in kilowatt-hours? c) Your electric company charges about a dime per kilowatt-hour. How much would your energy cost per day if you bought it from the power company? Could you feed yourself on this much money per day?

Part a. Step 1. Convert from Calories to joules.	Solution: (Section 14-1) One food Calorie = 1000 calories = 4180 joules (2500 Cal)(4180 J/Cal) = 1.0×10^7 J
Part b. Step 1. Convert from joules to kWh.	1 kWh = 3.6×10^6 J (1.0×10^7 J)(1 kWh/3.6×10^6 J) = 2.92 kWh
Part b. Step 2. Determine the cost of this energy in cents.	(2.92 kWh)[(10 cents)/kWh] = 29 cents

Part b. Step 3. Could you feed yourself on this money?	The answer is no.

TEXTBOOK PROBLEM 11. A 35 g glass thermometer reads 21.6°C before it is placed in 135 ml of water. When the water and thermometer come to equilibrium, the thermometer reads 39.2°C. What was the original temperature of the water?

Part a. Step 1. Determine the change temperature for each substance.	Solution: (Section 14-4) glass: $\Delta T_g = 39.2°C - 21.6°C = 17.6°C$ water: $\Delta T_w = 39.2°C - T_i$
Part a. Step 2. Determine the mass of the water and glass in kg.	mass of the glass = (35 g)(1kg/1000 g) = 0.035 kg, mass of water = (135 ml)(1.0 g/ml)(1kg/1000 g) = 0.135 kg
Part a. Step 3. Apply the law of conservation of energy to determine the initial temperature of the water.	heat gained by glass + heat lost by water = 0 heat gained by glass = - heat lost by water $m_g\, c_g\, \Delta T_g = -\ m_w\, c_w\, \Delta T_w$ [(0.035 kg)(0.200 kcal/kg°C)(17.6°C) = - (0.135 kg)(1.00 kcal/kg°C)](39.2°C - T_i) 0.123 kcal = - 5.29 kcal + (0.135 kcal/°C)T_i T_i = (5.4 kcal)/(0.135 kcal/°C) = 40.1°C

TEXTBOOK PROBLEM 17. When a 290 g piece of iron at 180°C is placed in a 95 g aluminum calorimeter cup containing 250 g of glycerin at 10°C, the final temperature is observed to be 38°C. What is the specific heat of glycerin? Note: the specific heat of iron is 0.11 kcal/kg °C, and the specific heat of aluminum is 0.22 kcal/kg °C.

Part a. Step 1. Determine the heat lost by the iron.	Solution: (Sections 14-4 and 14-5) heat lost = $m_{Fe}\, c_{Fe}\, \Delta T_{Fe}$

	$= (0.290\ kg)(0.11\ kcal/kg\ °C)(38°C - 180°C)$ heat lost = - 4.5 kcal
Part a. Step 2. Write an equation for the heat gained by the glycerin and the cup.	heat gained = $[m_{gly}\ c_{gly} + m_{Al}\ c_{Al}]\ (38°C - 10.0°C)$ $= [(0.25\ kg)\ c_{gly} + (0.095\ kg)(0.22\ kcal/kg°C)](28°C)$ heat gained = $(7.0\ kg\ °C)\ c_{gly} + 0.585\ kcal$
Part a. Step 3. Apply the law of conservation of energy and solve for c_{gly}.	heat gained + heat lost = 0 $(7.0\ kg\ °C)\ c_{gly} + 0.585\ kcal - 4.5\ kcal = 0$ $(7.0\ kg\ °C)\ c_{gly} = 3.91\ kcal$ $c_{gly} = (3.91\ kcal)/(7.0\ kg\ °C)$ $c_{gly} = 0.56\ \ kcal/kg\ °C = 2.3 \times 10^3\ J/kg\ °C$

TEXTBOOK PROBLEM 26. An iron boiler of mass 230 kg contains 830 kg of water at 18°C. A heater supplies energy at a rate of 52,000 kJ/h. How long does it take for the water (a) to reach the boiling point, and (b) to all have changed to steam?

Part a. Step 1. Use tables 14-1 and 14-3 in the textbook in order to complete a data table based on the information given.	Solution: (Section 14-5) $m_{water} = 830\ kg \quad m_{iron} = 230\ kg \quad c_{water} = 4180\ J/kg\cdot\ °C$ $c_{iron} = 450\ J/kg\cdot\ °C \quad L_V = 22.6 \times 10^5\ J/kg$ (for water) $\Delta T_w = \Delta T_{iron} = (100°C - 18\ °C) = 82\ C°$
Part a. Step 2. Determine the amount of energy (Q_1) required to raise the temperature to the boiling point.	$Q_1 = Q_{water} + Q_{iron}$ $Q_1 = m_w\ c_w\ \Delta T_w + m_{iron}\ c_{iron}\ \Delta T_{iron}$ but $\Delta T_w = \Delta T_{iron}$ $= [(830\ kg)(4180\ J/kg\cdot\ °C) + (230\ kg)(450\ J/kg\cdot\ °C)](100°C - 18°C)$ $= [3.47 \times 10^6\ J/°C + 1.04 \times 10^5\ J/°C]\ (82\ C°)$ $Q_1 = 2.93 \times 10^8\ J$

Part a. Step 3. Determine the time required for the water to reach the boiling point.	power = (energy required)/time $t_1 = Q_1/P$ where P = 52,000 kJ/h = 5.2×10^7 J/h $= (2.93 \times 10^8 \text{ J})/(5.2 \times 10^7 \text{ J/h})$ $t_1 = 5.6$ h
Part b. Step 1. Determine the energy (Q_2) required to change the water at 100°C to steam at 100°C.	$Q_2 = m L_V$ $= (830 \text{ kg})(22.6 \times 10^5 \text{ J/kg})$ $Q_2 = 1.88 \times 10^9$ J
Part b. Step 2. Determine the time (t_2) required to change the water at 100°C to steam.	power = energy required/time $t_2 = Q_2/P$ $= (1.88 \times 10^9 \text{ J})/(5.2 \times 10^7 \text{ J/h})$ $t_2 = 36$ h
Part b. Step 3. Determine the total time.	$t_{total} = t_1 + t_2$ $= 5.6 \text{ h} + 36 \text{ h}$ $t_{total} \approx 42$ h

TEXTBOOK PROBLEM 37. Two rooms, each a cube 4.0 m on a side, share a 12 cm thick brick wall. Because of a number of 100 watt light bulbs in one room, the air is at 30°C, while the other room is at 10°C. How many of the 100 W light bulbs are needed to maintain the temperature difference across the wall?

Part a. Step 1. Complete a data table and apply the equation for the rate of heat transfer through a substance.	Solution: (Sections 14-6, 14-7 and 14-8) $\ell = (12 \text{ cm})(1 \text{ m}/100 \text{ cm}) = 0.12$ m $A = 4.0 \text{ m} \times 4.0 \text{ m} = 16 \text{ m}^2$ $T_1 - T_2 = 30°\text{C} - 10°\text{C} = 20$ C° From Table 14-4 in the textbook, $k = 0.84$ J/s · m · C° $\Delta Q/\Delta t = k A (T_1 - T_2)/\ell$ $= (0.84 \text{ J/s} \cdot \text{m} \cdot \text{C°})(16 \text{ m}^2)(20 \text{ C°})/(0.12 \text{ m})$ $\Delta Q/\Delta t = 2240 \text{ J/s} = 2240$ W

Part a. Step 2. Determine the number of light bulbs required to maintain the temperature difference.	rate of heat transfer = number of light bulbs x power of each bulb 2240 W = n (100 W) n = 22.4 bulbs ≈ 23 light bulbs

TEXTBOOK PROBLEM 53. A mountain climber wears a goose down jacket 3.5 cm thick with a total surface area of 1.2 m^2. The temperature at the surface of the clothing is -20°C and at the skin is 34°C. Determine the rate of heat flow by conduction through the clothing (a) assuming that it is dry and the thermal conductivity, *k*, is that of down and (b) assuming the clothing is wet, so that *k* is that of water and the jacket is matted down to 0.50 cm thickness.

Part a. Step 1. Complete a data table and apply the equation for the conduction of heat through dry goose down.	Solution: (Section 14-6) $\ell = (3.5\ \text{cm})(1\ \text{m}/100\ \text{cm}) = 3.5 \times 10^{-2}\ \text{m} = 0.035\ \text{m}$ $A = 1.2\ \text{m}^2 \quad T_1 - T_2 = 34°\text{C} - -20°\text{C} = 54\ \text{C}°$ From Table 14-4 in the textbook, $k = 0.025\ \text{J/s} \cdot \text{m} \cdot \text{C}°$ $\Delta Q/\Delta t = k\,A\,(T_1 - T_2)/\ell$ $= (0.025\ \text{J/s} \cdot \text{m} \cdot \text{C}°)(1.2\ \text{m}^2)(54\ \text{C}°)/(0.035\ \text{m})$ $\Delta Q/\Delta t = 46\ \text{J/s} = 46\ \text{W}$
Part b. Step 1. Complete a new data table and apply the equation for the conduction of heat through wet goose down.	$\ell = (0.50\ \text{cm})(1\ \text{m}/100\ \text{cm}) = 0.0050\ \text{m}$ From Table 14-4 in the textbook, $k = 0.56\ \text{J/s} \cdot \text{m} \cdot \text{C}°$ $\Delta Q/\Delta t = k\,A\,(T_1 - T_2)/\ell$ $= (0.56\ \text{J/s} \cdot \text{m} \cdot \text{C}°)(1.2\ \text{m}^2)(54\ \text{C}°)/(0.0050\ \text{m})$ $\Delta Q/\Delta t = 7.3 \times 10^3\ \text{W}$

Note: based on the answer to part (b), the climber needs to change into dry clothing in a very short time or face the very real problem of losing his or her life due to hypothermia.