CHAPTER 5 THERMOCHEMISTRY

Reflect on Your Learning

(Page 296)

1. Absorbing energy: ice melting, water evaporating, photosynthesis.
   Releasing energy: water vapour condensing, respiration, combustion of gasoline.
2. Nuclear power plants, fossil fuel-burning power plants, hydroelectric power (largely from Niagara), solar power.
3. Both technologies drive turbines to generate electricity, but one uses falling water to drive the turbine and the other uses nuclear energy to create pressurized steam to drive the turbine.

Try This Activity: Burning Food

(Page 297)

(a) Use $q = mc\Delta T$ with student data.
(b) The heat released equalled the difference in potential energy of the reactants and products.
(c) Divide the heat by the mass of the nut.
(d) The reactants would be the same but the nut might not be completely digested, so there would be products other than carbon dioxide and water. The energy might be stored rather than released to the surroundings as heat. The process would be more efficient in terms of production of energy in useful forms, rather than heat.
(e) Much heat is lost to the surroundings, apart from the water in the can. Insulating the apparatus would improve results.

5.1 CHANGES IN MATTER AND ENERGY

PRACTICE

(Page 300)

Understanding Concepts

1. (a) chemical (new products: water and carbon dioxide)
   (b) physical (no new products)
   (c) chemical (new products: water and carbon dioxide)
   (d) physical (no new products)
   (e) chemical (new products: hydrogen gas and zinc chloride)
   (f) physical (no new products)
2.

System	Surroundings
(a) gas and oxygen	air and metal parts
(b) ice	hand
(c) gas and oxygen	air and metal parts
(d) wax	stove
(e) zinc and acid	beaker and water solvent
(f) ice	body part

3. All of these systems may be regarded as open because energy and/or matter may escape from the system, often in the form of gases. However, (a) may be considered a closed system for the instant at which the air–fuel mixture ignites.
4. The thimbleful has greater average thermal energy per molecule, but the pool has greater total thermal energy.
5. (a) exothermic
   (b) exothermic
   (c) endothermic

Making Connections

6. (a) Answers could include biological examples such as:
   - cellular respiration (chemical, exothermic, open);
   - combustion of fuel examples such as burning gasoline (chemical, exothermic, open);
   - change of state examples such as boiling water (physical, endothermic, open) or condensation (physical, exothermic, open);
   - household processes such as the use of drain cleaner (physical, exothermic, open).

   (b) Exothermic reactions are more common.
7. (a) 1 calorie = 4.18 J; 1 Calorie = 1000 calories = 4.18 kJ.
   (b) The reaction is controlled oxidation of food: a "slow burn" that releases energy.
   (c) Bomb calorimetry is used.

PRACTICE

(Page 302)

Understanding Concepts

8. Aluminum has the lowest specific heat capacity, which implies that it requires the least amount of heat to change temperature, and will undergo the greatest temperature change.
9. $q = mc\Delta T$

   $= 1.50 \text{ kg} \times 4.18 \text{ kJ/(kg•°C)} \times (98.7 - 18.0)\text{°C}$

   $q = 506 \text{ kJ}$
10. $m = \dfrac{q}{(c\Delta T)}$

    $= 80\,000 \text{ J/(4.18 kJ/(kg•°C)} \times 50\text{°C)}$

    $m = 383 \text{ g}$
11. $\Delta T = \dfrac{q}{(mc)}$

    $= 250\,000 \text{ J/(4000 g} \times 3.5 \text{ J/(g•°C))}$

    $\Delta T = 18\text{°C}$
12. (a) $q = mc\Delta T$

    $= 100 \text{ kg} \times 4.18 \text{ kJ/(kg•°C)} \times (45 - 10)\text{°C}$

    $q = 1.5 \times 10^4 \text{ kJ, or 15 MJ}$

    (b) money saved $= 14.6 \text{ MJ} \times 0.351¢\text{/MJ} \times 1500$

    $= 7.7 \times 10^3¢\text{, or \$77}$
13. (a) $q = mc\Delta T$

    $= 100 \text{ kg} \times 4.18 \text{ kJ/(kg•°C)} \times (75 - 45)\text{°C}$

    $q = 1.0 \times 10^4 \text{ kJ, or 10 MJ}$

    (b) money saved $= 10 \text{ MJ} \times 0.351¢\text{/MJ} \times 1500$

    $= 5.5 \times 10^3¢\text{, or \$55}$

PRACTICE

(Page 304)

Understanding Concepts

14. When a change occurs in a system, the potential energy change (ΔH) of the system is numerically equal to the change in thermal kinetic energy (q) of the surroundings.
15. Chemical changes have generally greater enthalpy changes than physical changes; nuclear changes have much greater enthalpy changes than chemical changes.

Applying Inquiry Skills

16. Experimental Design
    - A measured mass of the metal is added to a measured mass of dilute acid, and the temperature change in the solution is determined.
    - The heat gained by the solution is calculated using $q = mc\Delta T$.
    - The heat released per gram is calculated by dividing the heat by the mass of metal, and the result is compared to the three accepted values.

SECTION 5.1 QUESTIONS

(Page 305)

Understanding Concepts

1. Changes of state from solid to liquid, liquid to gas, and solid to gas are endothermic; changes of state from gas to liquid, liquid to solid, and gas to solid are exothermic.
2. mass, temperature change, specific heat capacity
3. (a) chemical (new products; rearrangement of atoms to new molecules)
   (b) physical (no new product; same molecules)
   (c) nuclear (uranium decays to form new atoms)
4.

System	Surroundings
(a) gasoline and oxygen	engine block and air
(b) water	air and remaining water
(c) uranium fuel	concrete

5. (a) open
   (b) open (because there is no container keeping the water vapour in contact with the liquid water)
   (c) isolated (although open if one considers the waste heat produced)
6. Energies per mol for physical, chemical, and nuclear changes are on the order of 101, 103, and 1011 kJ/mol, respectively.

Making Connections

7. See the Nelson *Chemistry 12* web site for possible useful sources of information. Bomb calorimeters are used to determine the energy content of foods, fuels, and even organisms in ecological food chains.
8. See the Nelson *Chemistry 12* web site for possible useful sources of information. Cold packs typically contain ammonium salts which, when mixed with water, absorb energy. Some hot packs contain iron filings which slowly oxidize in air and produce heat.

5.2 MOLAR ENTHALPIES

PRACTICE

(Page 308)

Understanding Concepts

1. amount of water, $n = 100.0\ \cancel{g} \times \frac{1\ \text{mol}}{18.0\ \cancel{g}}$

   $n = 5.56\ \text{mol}$

   $\Delta H = n\Delta H_{vap}$

   $= 5.56\ \cancel{\text{mol}} \times \frac{40.8\ \text{kJ}}{1\ \cancel{\text{mol}}}$

   $\Delta H = 227\ \text{kJ}$

2. molar mass of Freon, $M = 120.9$ g/mol

$$n_{Freon} = 500 \not{g} \times \frac{1 \text{ mol}}{120.9 \not{g}}$$

$$n_{Freon} = 4.14 \text{ mol}$$

$$\Delta H = n\Delta H_{vap}$$

$$= 4.14 \text{ mol} \times 34.99 \text{ kJ/mol}$$

$$\Delta H = 145 \text{ kJ}$$

3. amount of water, $n = 1.00 \times 10^6 \not{g} \times \dfrac{1 \text{ mol}}{18.0 \not{g}}$

$$n = 5.56 \times 10^4 \text{ mol}$$

$$\Delta H = n\Delta H_{vap}$$

$$= 5.56 \times 10^4 \text{ mol} \times 6.03 \text{ kJ/mol}$$

$$\Delta H = 3.35 \times 10^5 \text{ kJ}$$

PRACTICE

(Page 310)

Understanding Concepts

4. $q_{water} = mc\Delta T$

$$= 150 \text{ g} \times 4.18 \text{ J/g•°C} \times (20.4 - 16.7)\text{°C}$$

$$q_{water} = 2320 \text{ J, or } 2.32 \text{ kJ}$$

molar mass of urea, $M = 60.0$ g/mol

$$n_{urea} = 10.0 \not{g} \times \frac{1 \text{ mol}}{60 \not{g}}$$

$$n_{urea} = 0.167 \text{ mol}$$

$$n\Delta H_{solution} = q_{water}$$

$$\Delta H_{solution} = \frac{q_{water}}{n_{urea}}$$

$$= \frac{2.32 \text{ kJ}}{0.167 \text{ mol}}$$

$$\Delta H_{solution} = 13.9 \text{ kJ/mol}$$

Because the reaction is endothermic, $\Delta H_{solution}$ is +13.9 kJ/mol.

5. $q_{water} = mc\Delta T$

$$= 50.0 \text{ g} \times 4.18 \text{ J/g•°C} \times (27.8 - 24.0)\text{°C}$$

$$q_{water} = 794 \text{ J}$$

molar mass of gallium, $M = 69.72$ g/mol

$$n_{gallium} = 10.0 \text{ g} \times 1 \text{ mol/ } 69.72 \text{ g}$$

$$n_{gallium} = 0.143 \text{ mol}$$

$$n\Delta H_{solution} = q_{water}$$

$$\Delta H_{solution} = \frac{q_{water}}{n_{gallium}}$$

$$= \frac{794 \text{ J}}{0.143 \text{ mol}}$$

$$\Delta H_{solution} = 5.54 \times 10^3 \text{ J/mol or } 5.54 \text{ kJ/mol}$$

Because the reaction is exothermic, $\Delta H_{solution}$ is $-$ 5.54 kJ/mol.

PRACTICE

(Page 311)

Understanding Concepts

6. No heat is transferred to the outside environment; negligible heat is transferred to calorimeter materials; dilute aqueous solutions have the same specific heat capacity as water.
7. (a) $\Delta H_{vaporization}$

   (b) $\Delta H_{sublimation}$

   (c) $\Delta H_{solution}$

   (d) $\Delta H_{combustion}$

   (e) $\Delta H_{neutralization}$

Applying Inquiry Skills

8. Certainty is limited by the balance used to measure masses of reactants and solutions, graduated cylinders or other containers used to measure volumes of water and solutions, and thermometers used to measure temperature.
9. (a) $q_{water} = mc\Delta T$

   $= 500\text{ g} \times 4.18\text{ J/g•°C} \times (21.8 - 19.2)\text{°C}$

   $q_{water} = 5434\text{ J, or } 5.43\text{ kJ}$

   amount of $HCl_{(aq)}$, $n = MV$

   $= 11.6\text{ mol/L} \times 0.0431\text{ L}$

   $n = 0.500\text{ mol}$

   $n\Delta H_{dilution} = q_{water}$

   $\Delta H_{dilution} = \dfrac{q_{water}}{n}$

   $= \dfrac{5.43\text{ kJ}}{0.500\text{ mol}}$

   $\Delta H_{dilution} = 10.9\text{ kJ/mol}$

   Because the reaction is exothermic, $\Delta H_{dilution}$ is -10.9 kJ/mol.

   (b) The observed temperature increase would be too small, making the calculated ΔH too small.

   (c) The large amount of heat can cause the water to boil rapidly and spatter the acid solution about.
10. **Analysis**

   Assume 2.0 L of solution is 2000 g water.

   $q_{water} = mc\Delta T$

   $= 2000\text{ g} \times 4.18\text{ J/g•°C} \times (29.1 - 26.0)\text{°C}$

   $q_{water} = 25.9\text{ kJ}$

   amount of $Ba(NO_3)_{2(aq)}$, $n = 261\text{ g} \times \dfrac{1\text{ mol}}{261.3\text{ g}}$

   $n = 1.00\text{ mol}$

   $n\Delta H_{reaction} = q_{water}$

   $\Delta H_{reaction} = \dfrac{q_{water}}{n}$

   $= \dfrac{25.9\text{ kJ}}{1.00\text{ mol}}$

   $\Delta H_{reaction} = 25.9\text{ kJ/mol } Ba(NO_3)_{2(aq)}$

   Because the reaction is exothermic, $\Delta H_{reaction}$ is -26 kJ/mol.

SECTION 5.2 QUESTIONS

(Page 312)

Understanding Concepts

1. (a) $q = n\Delta H_{comb}$

$= 5.0 \text{ mol} \times 1.56 \text{ MJ/mol}$

$q = 7.8 \text{ MJ}$

(b) molar mass of ethane, $(C_2H_6) = 30.0 \text{ g/mol}$

$q = n\Delta H^\circ_{comb}$

$= 40.0 \text{ g} \times (1 \text{ mol}/ 30.0 \text{ g}) \times (1.56 \text{ MJ/mol})$

$q = 2.08 \text{ MJ}$

2. $q_{water} = n\Delta H^\circ_{solution}$

$= 40.0 \text{ g } NH_4Cl \times 1 \text{ mol}/53.5 \text{ g} \times 14.8 \text{ kJ/mol}$

$q_{water} = 11.1 \text{ kJ}$

$\Delta T = \dfrac{q}{mc}$

$= \dfrac{11\ 100}{(200.0 \times 4.18)}$

$\Delta T = 13.2°C$

Since the dissolving is endothermic, the temperature of the water will fall.

$T_f = T_i - \Delta T$

$= 25 - 13$

$T_f = 12°C$

3. $q_{water} = mc\Delta T$

$= 500.0 \text{ g} \times 4.18 \text{ J/g•°C} \times (55.0 - 20.0)°C$

$q_{water} = 71\ 750 \text{ J} = 0.0718 \text{ MJ}$

molar mass of decane, $M = 142$ g

$n\Delta H_{combustion} = q_{water}$

amount of decane, $n = \dfrac{q}{\Delta H_{combustion}}$

$= \dfrac{0.0718 \text{ MJ}}{6.78 \text{ MJ/mol}}$

$n = 0.0106 \text{ mol}$

mass decane, $m = 0.0106 \text{ mol} \times 142 \text{ g/mol}$

$m = 1.50 \text{ g}$

4. molar mass of salt, $M = 322.1 \text{ g/mol}$

amount of salt, $n = 1000 \text{ g} \times (1 \text{ mol}/322.1 \text{ g})$

$n = 3.10 \text{ mol}$

$\Delta H = n\Delta H_{solid}$

$= 3.10 \text{ mol} \times 78.0 \text{ kJ}/1 \text{ mol}$

$\Delta H = 242 \text{ kJ}$

Applying Inquiry Skills

5. Assume that 200 mL of solution is 200 g water.

$$q_{\text{water}} = mc\Delta T$$
$$= 200\text{ g} \times 4.18\text{ J/g•°C} \times (28.1 - 21.0)\text{°C}$$
$$q_{\text{water}} = 5.94\text{ kJ}$$

amount of KOH $= n$

$$= 5.2\text{ g} \times 1\text{ mol/}56.1\text{ g}$$
$$n = 0.0927\text{ mol}$$

$$n\Delta H_{\text{reaction}} = q_{\text{water}}$$
$$\Delta H_{\text{reaction}} = \frac{q_{\text{water}}}{n}$$
$$= \frac{5.94\text{ kJ}}{0.0927\text{ mol}}$$

$\Delta H_{\text{reaction}} = 64$ kJ/mol ~~$Ba(NO_3)_2$~~ KOH

Because the reaction is exothermic, $\Delta H_{\text{reaction}}$ is -64 kJ/mol.

6. Answers will vary, but the student could use a polystyrene (Styrofoam) coffee cup calorimeter and thermometer to investigate temperature changes that occurred when the dextrose tablets were added to water. A mortar and pestle might be used to simulate the grinding process that occurs in chewing. Ambitious students might even investigate whether there was any effect of amylase (found in saliva) on the process.

Making Connections

7. See the Nelson *Chemistry 12* web site for possible useful sources of information. In general, the propane is used to vaporize and separate the components of an aqueous ammonia mixture. The ammonia gas then goes through cycles of condensation (outside the compartment, releasing heat to the air) and evaporation inside the compartment (absorbing heat from food).

5.3 REPRESENTING ENTHALPY CHANGES

PRACTICE

(Page 319)

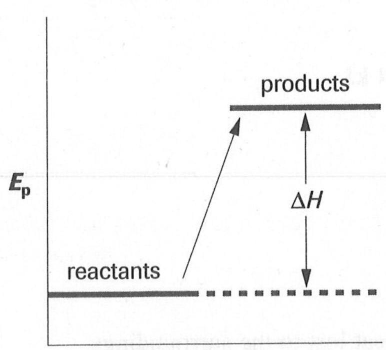
Understanding Concepts

1. (a) $2\,C_{(s)} + H_{2(g)} + 228\text{ kJ} \rightarrow C_2H_{2(g)}$

$2\,C_{(s)} + H_{2(g)} \rightarrow C_2H_{2(g)} \quad \Delta H = +228\text{ kJ}$

$\Delta H^{\circ}_{f} = +228$ kJ/mol acetylene

Endothermic Reaction

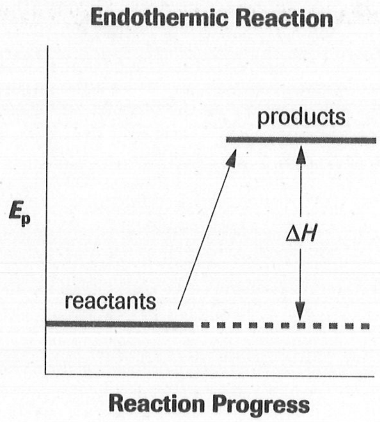


Reaction Progress

(b) $Al_2O_{3(s)} + 1676\ kJ \rightarrow 2\ Al_{(s)} + 3/2\ O_{2(g)}$

$Al_2O_{3(s)} \rightarrow 2\ Al_{(s)} + 3/2\ O_{2(g)} \quad \Delta H = +1676\ kJ$

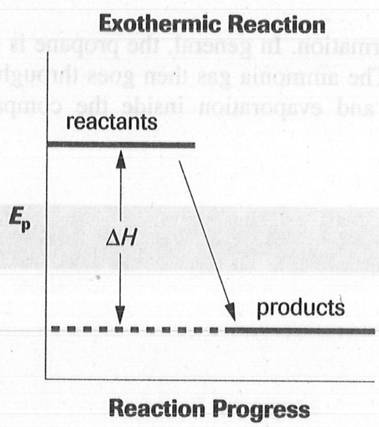
$\Delta H^\circ_{decomp} = +1676$ kJ/mol aluminum oxide



(c) $C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} + 393.5\ kJ$

$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \quad \Delta H = -393.5\ kJ$

$\Delta H^\circ_{comb} = -393.5$ kJ/mol carbon



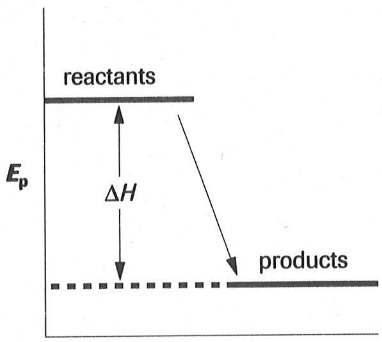
2. (a) $\Delta H_{comb} = -241.8$ kJ/mol H_2
   (b) $\Delta H_{comb} = -283.6$ kJ/mol NH_3
   (c) $\Delta H_{comb} = +81.6$ kJ/mol N_2
   (d) $\Delta H_{comb} = -372.8$ kJ/mol Fe
3. (a) $\Delta H = -114$ kJ
   (b) $H_2SO_{4(aq)} + 2\ NaOH_{(aq)} \rightarrow Na_2SO_{4(aq)} + 2\ H_2O_{(l)} \quad \Delta H = -114\ kJ$
   (c) $\Delta H_{neut} = -114$ kJ/mol H_2SO_4
   (d) $\Delta H_{neut} = -57$ kJ/mol NaOH
4. (a) $H_{2(g)} + 1/2\ O_{2(g)} \rightarrow H_2O_{(g)} \quad \Delta H = -241.8\ kJ$
   $H_2O_{(g)} \rightarrow H_{2(g)} + 1/2\ O_{2(g)} \quad \Delta H = +241.8\ kJ$
   (b) Such equations have the same enthalpy change with a different sign.
5. (a) The reaction is exothermic because potential energy is converted to heat lost to the surroundings.
   (b) The reaction is endothermic because heat absorbed from the surroundings is converted to potential energy.

SECTION 5.3 QUESTIONS

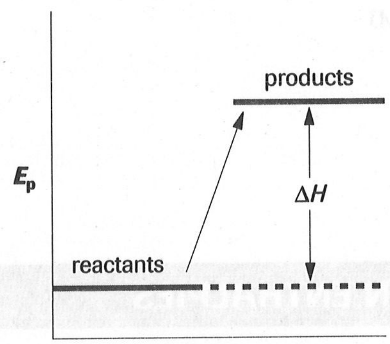
(Page 320)

Understanding Concepts

1. (a) Since the reaction is exothermic, the PE diagram will resemble this. Reactants are octane and oxygen; the products are carbon dioxide and water.



(b) Since the reaction is endothermic, the PE diagram will resemble this. Reactants are boron and hydrogen; the product is diborane.



2. (a) $Mg_{(s)} + O_{2(g)} + H_{2(g)} \rightarrow Mg(OH)_{(s)} \quad \Delta H = -925 \text{ kJ}$

(b) $C_5H_{12(g)} + 8\,O_{2(g)} \rightarrow 5\,CO_{2(g)} + 6\,H_2O_{(g)} \quad \Delta H° = -2018 \text{ kJ}$

(c) $NiO_{(s)} \rightarrow Ni_{(s)} + 1/2\,O_{2(g)} \quad \Delta H° = 240 \text{ kJ}$

3. (a) $C_4H_{10(g)} + 13/2\,O_{2(g)} \rightarrow 4\,CO_{2(g)} + 5\,H_2O_{(g)} + 2.87 \text{ MJ}$

(b) $C_{(graphite)} + 2 \text{ kJ} \rightarrow C_{(diamond)}$

(c) $C_2H_6O_{(l)} + 3\,O_{2(g)} \rightarrow 2\,CO_{2(g)} + 3\,H_2O_{(g)} + 1.28 \text{ MJ}$

Applying Inquiry Skills

4. **Analysis**

(a) $q_{water} = mc\Delta T$

$= 200.0 \text{ g} \times 4.18 \text{ J/(g•°C)} \times (76.0 - 21.0)\text{°C}$

$q_{water} = 45.9(8) \text{ kJ}$ [Digit in parentheses will be lost in rounding.]

$q_{copper} = mc\Delta T$

$= 50.0\ g \times 0.385\ J/(g{\bullet}°C) \times (76.0 - 21.0)°C$

$q_{copper} = 1.06\ kJ$

$n\Delta H_{reaction} = q_{total}$

$= q_{water} + q_{copper}$

$n\Delta H_{reaction} = 47.0(4)\ kJ$ [Digit in parentheses will be lost in rounding.]

$m_{eicosane} = 8.567 - 7.357\ g$

$m_{eicosane} = 1.21\ g$

$M_{eicosane\ (C_{20}H_{42})} = 282\ g/mol$

$n_{eicosane} = 1.21\ g \times \frac{1\ mol}{282\ g}$

$n_{eicosane} = 4.29 \times 10^{-3}\ mol$

$\Delta H_{comb} = \frac{q_{total}}{n}$

$= \frac{47.0(4)\ kJ}{4.29 \times 10^{-3}\ mol}$

$\Delta H_{comb} = 1.10 \times 10^{4}\ kJ/mol\ C_{20}H_{42}$

Because the reaction is exothermic, $\Delta H_{reaction}$ is –11.0 MJ/mol.

(b) The reaction was exothermic, because heat was released to the surroundings and the temperature increased.

(c) $C_{20}H_{42(s)} + 61/2\ O_{2(g)} \rightarrow 20\ CO_{2(g)} + 21\ H_2O_{(g)} + 11.0\ MJ$

$C_{20}H_{42(s)} + 61/2\ O_{2(g)} \rightarrow 20\ CO_{2(g)} + 21\ H_2O_{(g)} \quad \Delta H = -11.0\ MJ$

Evaluation

(d) Percentage error $= \frac{(13.3 - 11.0)}{13.3} \times 100$

$= 17\%$

5.4 HESS'S LAW OF ADDITIVITY OF REACTION ENTHALPIES

PRACTICE

(Page 326)

Understanding Concepts

1. **1 × (1):** $2\ Al_{(s)} + \frac{3}{2}\ O_{2(g)} \rightarrow Al_2O_{3(s)} \qquad \Delta H = (1)(-1675.7)\ kJ$

–1 × (2): $Fe_2O_{3(s)} \rightarrow 2\ Fe_{(s)} + \frac{3}{2}\ O_{2(g)} \qquad \Delta H = (-1)(-824.2)\ kJ$

$Fe_2O_{3(s)} + 2\ Al_{(s)} \rightarrow Al_2O_{3(s)} + 2\ Fe_{(s)} \qquad \Delta H = -851.5\ kJ$

2. $\frac{1}{2}$ **× (1):** $C_{(s)} + \frac{1}{2}\ O_{2(g)} \rightarrow CO_{(g)} \qquad \Delta H = (\frac{1}{2})(-221.0)\ kJ$

$-\frac{1}{2}$ **× (2):** $H_2O_{(g)} \rightarrow H_{2(g)} + \frac{1}{2}\ O_{2(g)} \qquad \Delta H = (-\frac{1}{2})(-483.6)\ kJ$

$H_2O_{(g)} + C_{(s)} \rightarrow CO_{(g)} + H_{2(g)} \qquad \Delta H = 131.3\ kJ$