(f) Mass measurements are in general more accurate than volume measurements for solids. The volume depends on the size of the particles and how tightly the solid is packed into a measuring spoon or cup. However, for small quantities it is much easier, faster, and requires less expensive equipment to measure volumes than masses. (People who bake use specific techniques and spoons to minimize the problem of varying density of solids.)

5.1 QUANTITATIVE ANALYSIS

PRACTICE

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Understanding Concepts

1. In a quantitative (complete) reaction of two reactants, both cannot be in excess. If both are present in stoichiometric ratio quantity, neither would, strictly speaking, be the limiting reagent (or both would ...).
2. A would have to be limiting. B would have to be reacted in excess, to ensure that all of A reacts — so that subsequent calculations would correctly indicate how much A was originally present.

PRACTICE

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Making Connections

3. A typical report might deal with the recently developed highly complex blood/urine analysis for recombinant human erythropoietin. EPO is a substance that can be used (illegally) by athletes to artificially increase production of red blood cells, which improves the oxygen-carrying capacity of the blood, and thus improves performance in endurance sports. The correlated career would be that of a sports-related laboratory analyst, or of a research scientist (in one example an Australian, Canadian, Chinese, and Norwegian team, working for Bayer corporation at a research centre in New York state).
4. A typical career might be that of a process and quality control analyst for any chemical industry. Such a career usually requires certification from a postsecondary technical institution.

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PRACTICE

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Applying Inquiry Skills

5. A standard curve is a graph of the relationship between quantities of any two substances involved in a quantitative stoichiometric chemical reaction. Such a curve is used to quickly predict the quantity of one of the substances when the quantity of the other is known.
6. (a) Successive 10-mL samples (aliquots) of sodium sulfide solution should be added to the lead(II) nitrate solution, allowing the precipitate to settle each time, until addition of the next aliquot causes no reaction. The total volume of sodium sulfide solution used is then in excess.
   (b) The mass of lead(II) nitrate should be the dependent variable (*y*-axis) and the mass of lead(II) sulfide should be the independent variable (*x*-axis).

Making Connections

7. The postal data could be used to make a bar graph but not a standard curve, because the postal service charges the same cost for a range of masses.

SECTION 5.1 QUESTIONS

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Understanding Concepts

1. (a) B is the limiting reagent.

   (b)
$$\begin{array}{cccccc} 1\text{ A} & + & 1\text{ B} & \rightarrow & 2\text{ C} \\ & & 2.1\text{ mol} & & n \end{array}$$

$$n_C = 2.1\ \cancel{\text{mol}}\text{ B} \times \frac{2\text{ mol C}}{1\ \cancel{\text{mol}}\text{ B}}$$

$$n_C = 4.2\text{ mol}$$

   The amount of C formed will be 4.2 mol.

2.
$$\begin{array}{lllllllll} CH_{4(g)} & + & 2\ O_{2(g)} & \rightarrow & CO_{2(g)} & + & 2\ H_2O_{(g)} \\ 32\text{ g} & & m & & & & \\ 16.05\text{ g/mol} & & 32.00\text{ g/mol} & & & & \end{array}$$

$$n_{CH_4} = 32\ \cancel{\text{g}} \times \frac{1\text{ mol}}{16.05\ \cancel{\text{g}}}$$

$$n_{CH_4} = 2.0\text{ mol}$$

$$n_{O_2} = 2.0\text{ mol} \times \frac{2}{1} \qquad (\text{mole ratio } O_2 : CH_4 \text{ is } 2:1)$$

$$n_{O_2} = 4.0\text{ mol}$$

$$m_{O_2} = 4.0\ \cancel{\text{mol}} \times \frac{32.00\text{ g}}{1\ \cancel{\text{mol}}}$$

$$m_{O_2} = 1.3 \times 10^2\text{ g} = 0.13\text{ kg}$$

   or

$$m_{O_2} = 32\ \cancel{\text{g}}\ \cancel{CH_4} \times \frac{1\ \cancel{\text{mol}}\ \cancel{CH_4}}{16.05\ \cancel{\text{g}}\ \cancel{CH_4}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{O_2}}{1\ \cancel{\text{mol}}\ \cancel{CH_4}} \times \frac{32.00\text{ g } O_2}{1\ \cancel{\text{mol}}\ \cancel{O_2}}$$

$$m_{O_2} = 1.3 \times 10^2\text{ g} = 0.13\text{ kg}$$

   The minimum mass of oxygen required for complete combustion would be 0.13 kg. A 10% excess would be 0.13 kg × 110% = 0.14 kg.

3. A standard curve is a graph of the relationship between quantities of any two substances involved in a quantitative stoichiometric chemical reaction. If the curve is plotted empirically, from repeated mass measurements, the reaction equation becomes irrelevant.

Applying Inquiry Skills

4. The limiting reagent must be measured accurately, because the predictive calculation is made from this value.
5. Successive samples (aliquots) of excess reagent solution should be added to the limiting reagent solution, allowing the precipitate to settle each time, until addition of the next aliquot causes no reaction. The total volume of excess reagent solution used is then empirically in excess.
6. Several reactions must be done with samples of aluminum of varying masses, and excess copper(II) sulfate solution each time. From the measured mass of copper produced each time, an average copper/aluminum mass ratio can be calculated, and used to draw a standard "curve" for this reaction.

Making Connections

7. Almost all everyday and workplace situations that involve a quantity ratio are now performed by calculators, rather than by use of tables or graphs. Everyday examples include cooking quantities and automobile mileage; while work examples might be quantities used in photofinishing, or mixing herbicide solutions on a farm, or a whole host of other examples.

5.2 BALANCING CHEMICAL EQUATIONS

PRACTICE

(Page 211)

Understanding Concepts

1. Conservation of mass requires that a reaction equation somehow represent the fact that total reactant mass equals total product mass.
2. (a) $Mg_{(s)} + 2\ HCl_{(aq)} \rightarrow MgCl_{2(aq)} + H_{2(g)}$

   (b) $2\ Na_{(s)} + 2\ H_2O_{(l)} \rightarrow 2\ NaOH_{(aq)} + H_{2(g)}$

   (c) $CaCO_{3(s)} + 2\ HCl_{(aq)} \rightarrow CaCl_{2(s)} + H_2O_{(l)} + CO_{2(g)}$

   (d) $Cu_{(s)} + 4\ HNO_{3(aq)} \rightarrow Cu(NO_3)_{2(aq)} + 2\ NO_{(g)} + 2\ H_2O_{(l)}$

   (e) $2\ C_3H_{6(g)} + 9\ O_{2(g)} \rightarrow 6\ CO_{2(g)} + 6\ H_2O_{(g)}$
3. (a) $2\ H_{2(g)} + O_{2(g)} \rightarrow 2\ H_2O_{(g)}$

   (b) Correct

   (c) $Pb_{(s)} + 2\ AgNO_{3(aq)} \rightarrow 2\ Ag_{(s)} + Pb(NO_3)_{2(aq)}$

   (d) Correct
4. $Fe(NO_3)_{3(aq)}\ 1\ 3\ LiOH_{(aq)} \rightarrow 3\ LiNO_{3(aq)}\ 1\ Fe(OH)_{3(s)}$

PRACTICE

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Understanding Concepts

5. The formula coefficients of a chemical equation represent the mole ratio of substances in the reaction.
6. Consider: $C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$
   This reaction equation shows clearly that the number of moles of substances in reactions is not conserved: two moles of reactants become one mole of product.
7. $3\ NO_{2(g)} + H_2O_{(l)} \rightarrow 2\ HNO_{3(aq)} + NO_{(g)}$

   The mole ratio is 3:1:2:1 for the reaction equation as written here.
8. In a chemical industry, the amounts produced and consumed in reactions determine the economics of the process — so the mole ratio is essential knowledge for determining whether any process is practical.

PRACTICE

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Understanding Concepts

9. Fertilizers increase crop production. Without them there would not be enough food produced to support the current population of the Earth.
10. Fertilizer excess that enters the environment can cause serious changes in watersheds, affecting all living things that depend on that water supply.

Making Connections

11. Typical reports might select groups like Ducks Unlimited, Canada, which is dedicated to actively working to preserve Canada's wetlands. DU emphasize that not only do wetlands provide habitat for a complex ecosystem of living things; they act as natural filters for our water supply.

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Explore an Issue Role Play: Controlling the Use of Fertilizers

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SECTION 5.2 QUESTIONS

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Understanding Concepts

1. Balancing by inspection uses a trial-and-error approach to determining the coefficients of a reaction equation.
2. (a) $2\ Al_{(s)} + 3\ CuCl_{2(aq)} \rightarrow 3\ Cu_{(s)} + 2\ AlCl_{3(aq)}$
   (b) $Cu_{(s)} + 2\ HCl_{(aq)} \rightarrow H_{2(g)} + CuCl_{2(aq)}$
   (c) $2\ HgO_{(s)} \rightarrow 2\ Hg_{(l)} + O_{2(g)}$
   (d) $CH_{4(g)} + H_2O_{(g)} \rightarrow CO_{(g)} + 3\ H_{2(g)}$ (step i)
   $CO_{(g)} + 2\ H_{2(g)} \rightarrow CH_3OH_{(g)}$ (step ii)
3. (a) $C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$
   (b) $S_{8(s)} + 8\ O_{2(g)} \rightarrow 8\ SO_{2(g)}$
   (c) $Cu(OH)_{2(s)} + H_2SO_{4(aq)} \rightarrow 2\ H_2O_{(l)} + CuSO_{4(aq)}$
   (d) $CaSiO_{3(s)} + H_2SO_{3(aq)} \rightarrow H_2SiO_{3(aq)} + CaSO_{3(s)}$
   (e) $CaCO_{3(s)} + 2\ HNO_3 \rightarrow H_2CO_{3(aq)} + Ca(NO_3)_{2(aq)}$
   (f) $2\ Al_{(s)} + 3\ H_2SO_{4(aq)} \rightarrow 3\ H_{2(g)} + Al_2(SO_4)_{3(aq)}$
   (g) $SO_{2(g)} + H_2O_{(l)} \rightarrow H_2SO_{3(aq)}$
   (h) $2\ Fe_{(s)} + 3\ H_2SO_{3(aq)} \rightarrow 3\ H_{2(g)} + Fe_2(SO_3)_{3(s)}$
   (i) $N_{2(g)} + O_{2(g)} \rightarrow 2\ NO_{(g)}$
   (j) $CO_{2(g)} + H_2O_{(l)} \rightarrow H_2CO_{3(aq)}$
   (k) $CH_{4(g)} + 2\ O_{2(g)} \rightarrow CO_{2(g)} + 2\ H_2O_{(g)}$
   (l) $2\ C_4H_{10(g)} + 13\ O_{2(g)} \rightarrow 8\ CO_{2(g)} + 10\ H_2O_{(g)}$
   (m) $2\ FeS_{(s)} + 3\ O_{2(g)} \rightarrow 2\ FeO_{(s)} + 2\ SO_{2(g)}$
   (n) $2\ H_2S_{(g)} + 3\ O_{2(g)} \rightarrow 2\ H_2O_{(g)} + 2\ SO_{2(g)}$
   (o) $2\ CaCO_{3(s)} + 2\ SO_{2(g)} + O_{2(g)} \rightarrow 2\ CaSO_{4(s)} + 2\ CO_{2(g)}$
4. (a) $4\ CH_3NO_{2(l)} + 7\ O_{2(g)} \rightarrow 4\ CO_{2(g)} + 6\ H_2O_{(g)} + 4\ NO_{2(g)}$
   The mole ratio is 4:7:4:6:4 for the reaction equation as written here.
   (b) $2\ Al_{(s)} + 3\ CuCl_{2(aq)} \rightarrow 3\ Cu_{(s)} + 2\ AlCl_{3(aq)}$
   The mole ratio is 2:3:3:2 for the reaction equation as written here.

Making Connections

5. Fertilizers are sold with information about what area can be treated per kilogram. Farmers would have to do area calculations, cost calculations, and predictive calculations about the value of projected increased crop yield.

(c) ${}^{187}_{75}\text{Re} \rightarrow {}^{187}_{76}\text{Os} + {}^{0}_{-1}\text{e}$

(d) ${}^{11}_{5}\text{B} + {}^{1}_{1}\text{p} \rightarrow 3\ {}^{4}_{2}\text{He}$

(e) ${}^{98}_{42}\text{Mo} + {}^{2}_{1}\text{H} \rightarrow {}^{99}_{43}\text{Tc} + {}^{1}_{0}\text{n}$

7. The mass number drops by 28, and only alpha decay drops the mass number, and each alpha particle is 4, so 7 alpha particles are emitted. The atomic number drops by 10, which is 4 less than the drop of 14 caused by the alpha decays, so there must be 4 beta particles emitted, because each one raises the atomic number by 1.

Making Connections

8. A typical report would include information on directing a particle beam through the body to cause maximum damage at a tumour location — and probably on the development of the "cobalt bomb" cobalt-60 cancer therapy machines by AECL, and the extensive worldwide use of this treatment program.

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5.4 CALCULATING MASSES OF REACTANTS AND PRODUCTS

PRACTICE

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Understanding Concepts

1.
$$\begin{array}{llll} 2\,\text{Al}_2\text{O}_{3(s)} & \rightarrow\quad 3\,\text{O}_{2(g)} & + & 4\,\text{Al}_{(s)} \\ 125\text{ g} & & & m \\ 101.96\text{ g/mol} & & & 26.98\text{ g/mol} \end{array}$$

$$\begin{aligned} n_{\text{Al}_2\text{O}_3} &= 125\ \cancel{\text{g}} \times \frac{1\text{ mol}}{101.96\ \cancel{\text{g}}} \\ n_{\text{Al}_2\text{O}_3} &= 1.23\text{ mol} \\ n_{\text{Al}} &= 1.23\text{ mol} \times \frac{4}{2} \\ n_{\text{Al}} &= 2.45\text{ mol} \\ m_{\text{Al}} &= 2.45\ \cancel{\text{mol}} \times \frac{26.98\text{ g}}{1\ \cancel{\text{mol}}} \\ m_{\text{Al}} &= 66.2\text{ g} \end{aligned}$$

or

$$\begin{aligned} m_{\text{Al}} &= 125\ \cancel{\text{g}}\ \cancel{\text{Al}_2\text{O}_3} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{Al}_2\text{O}_3}}{101.96\ \cancel{\text{g}}\ \cancel{\text{Al}_2\text{O}_3}} \times \frac{4\ \cancel{\text{mol}}\ \cancel{\text{Al}}}{2\ \cancel{\text{mol}}\ \cancel{\text{Al}_2\text{O}_3}} \times \frac{26.98\text{ g Al}}{1\ \cancel{\text{mol}}\ \cancel{\text{Al}}} \\ m_{\text{Al}} &= 66.2\text{ g} \end{aligned}$$

The (maximum) mass of aluminum that can be produced is 66.2 g.

2.
$$\begin{array}{llllll} \text{C}_3\text{H}_{8(g)} & +\quad 5\,\text{O}_{2(g)} & \rightarrow & 3\,\text{CO}_{2(g)} & + & 4\,\text{H}_2\text{O}_{(g)} \\ 10.0\text{ g} & m & & & & \\ 44.11\text{ g/mol} & 32.00\text{ g/mol} & & & & \end{array}$$

$$\begin{aligned} n_{\text{C}_3\text{H}_8} &= 10.0\ \cancel{\text{g}} \times \frac{1\text{ mol}}{44.11\ \cancel{\text{g}}} \\ n_{\text{C}_3\text{H}_8} &= 0.227\text{ mol} \\ n_{\text{O}_2} &= 0.227\text{ mol} \times \frac{5}{1} \\ n_{\text{O}_2} &= 1.13\text{ mol} \\ m_{\text{O}_2} &= 1.13\ \cancel{\text{mol}} \times \frac{32.00\text{ g}}{1\ \cancel{\text{mol}}} \end{aligned}$$

$$m_{O_2} = 36.3\ g$$

or

$$\begin{aligned} m_{O_2} &= 10.0\ \cancel{g}\ \cancel{C_3H_8} \times \frac{1\ \cancel{mol}\ \cancel{C_3H_8}}{44.11\ \cancel{g}\ \cancel{C_3H_8}} \times \frac{5\ \cancel{mol}\ \cancel{O_2}}{1\ \cancel{mol}\ \cancel{C_3H_8}} \times \frac{32.00\ g\ O_2}{1\ \cancel{mol}\ \cancel{O_2}} \\ m_{O_2} &= 36.3\ g \end{aligned}$$

The (minimum) mass of oxygen required is 36.3 g.

3.
$$\begin{array}{lllllll} 2\ NaCl_{(aq)} & + & Pb(NO_3)_{2(aq)} & \rightarrow & 2\ NaNO_{3(aq)} & + & PbCl_{2(s)} \\ 2.57\ g & & & & & & m \\ 58.44\ g/mol & & & & & & 278.10\ g/mol \end{array}$$

$$\begin{aligned} n_{NaCl} &= 2.57\ \cancel{g} \times \frac{1\ mol}{58.44\ \cancel{g}} \\ n_{NaCl} &= 0.0440\ mol \\ n_{PbCl_2} &= 0.0440\ mol \times \frac{1}{2} \\ n_{PbCl_2} &= 0.0220\ mol \\ m_{PbCl_2} &= 0.0220\ \cancel{mol} \times \frac{278.10\ g}{1\ \cancel{mol}} \\ m_{PbCl_2} &= 6.11\ g \end{aligned}$$

or

$$\begin{aligned} m_{PbCl_2} &= 2.57\ \cancel{g}\ \cancel{NaCl} \times \frac{1\ \cancel{mol}\ \cancel{NaCl}}{58.44\ \cancel{g}\ \cancel{NaCl}} \times \frac{1\ \cancel{mol}\ \cancel{PbCl_2}}{2\ \cancel{mol}\ \cancel{NaCl}} \times \frac{278.10\ g\ PbCl_2}{1\ \cancel{mol}\ \cancel{PbCl_2}} \\ m_{PbCl_2} &= 6.11\ g \end{aligned}$$

The (maximum) mass of lead(II) chloride produced would be 6.11 g.

4.
$$\begin{array}{lllllll} 2\ Al_{(s)} & + & 3\ H_2SO_{4(aq)} & \rightarrow & 3\ H_{2(g)} & + & 2\ Al_2(SO_4)_{3(aq)} \\ 2.73\ g & & & & m & & \\ 26.98\ g/mol & & & & 2.02\ g/mol & & \end{array}$$

$$\begin{aligned} n_{Al} &= 2.73\ \cancel{g} \times \frac{1\ mol}{26.98\ \cancel{g}} \\ n_{Al} &= 0.101\ mol \\ n_{H_2} &= 0.101\ mol \times \frac{3}{2} \\ n_{H_2} &= 0.152\ mol \\ m_{H_2} &= 0.152\ \cancel{mol} \times \frac{2.02\ g}{1\ \cancel{mol}} \\ m_{H_2} &= 0.307\ g \end{aligned}$$

or

$$\begin{aligned} m_{H_2} &= 2.73\ \cancel{g}\ \cancel{Al} \times \frac{1\ \cancel{mol}\ \cancel{Al}}{26.98\ \cancel{g}\ \cancel{Al}} \times \frac{3\ \cancel{mol}\ \cancel{H_2}}{2\ \cancel{mol}\ \cancel{Al}} \times \frac{2.02\ g\ H_2}{1\ \cancel{mol}\ \cancel{H_2}} \\ m_{H_2} &= 0.307\ g \end{aligned}$$

The (predicted) mass of hydrogen would be 0.307 g, or 307 mg.

5.
$$\begin{array}{lllllll} 2\ KOH_{(aq)} & + & Cu(NO_3)_{2(aq)} & \rightarrow & 2\ KNO_{3(aq)} & + & Cu(OH)_{2(s)} \\ 2.67\ g & & & & & & m \\ 56.11\ g/mol & & & & & & 97.57\ g/mol \end{array}$$

$$\begin{aligned} n_{KOH} &= 2.67\ \cancel{g} \times \frac{1\ mol}{56.11\ \cancel{g}} \\ n_{KOH} &= 0.0476\ mol \\ n_{Cu(OH)_2} &= 0.0476\ mol \times \frac{1}{2} \\ n_{Cu(OH)_2} &= 0.0238\ mol \\ m_{Cu(OH)_2} &= 0.0238\ \cancel{mol} \times \frac{97.57\ g}{1\ \cancel{mol}} \end{aligned}$$

$m_{Cu(OH)_2} = 2.32\text{ g}$

or

$$m_{Cu(OH)_2} = 2.67\ \cancel{g}\ \cancel{KOH} \times \frac{1\ \cancel{mol}\ \cancel{KOH}}{56.11\ \cancel{g}\ \cancel{KOH}} \times \frac{1\ \cancel{mol}\ \cancel{Cu(OH)_2}}{2\ \cancel{mol}\ \cancel{KOH}} \times \frac{97.57\text{ g Cu(OH)}_2}{1\ \cancel{mol}\ \cancel{Cu(OH)_2}}$$

$m_{Cu(OH)_2} = 2.32\text{ g}$

The mass of copper(II) hydroxide produced would be 2.32 g.

6. $2\ H_2O_{(l)} \rightarrow 2\ H_{2(g)} + O_{2(g)}$
   25.0 g $\quad$ N
   18.02 g/mol $\quad$ 6.02×10^{23} molecules/mol

$$n_{H_2O} = 25.0\ \cancel{g} \times \frac{1\text{ mol}}{18.02\ \cancel{g}}$$

$$n_{H_2O} = 1.39\text{ mol}$$

$$n_{O_2} = 1.39\text{ mol} \times \frac{1}{2}$$

$$n_{O_2} = 0.694\text{ mol}$$

$$N_{O_2} = 0.694\ \cancel{mol} \times \frac{6.02 \times 10^{23}\text{ molecules}}{1\ \cancel{mol}}$$

$$N_{O_2} = 4.18 \times 10^{23}\text{ molecules}$$

or

$$N_{O_2} = 25.0\ \cancel{g}\ \cancel{H_2O} \times \frac{1\ \cancel{mol}\ \cancel{H_2O}}{18.02\ \cancel{g}\ \cancel{H_2O}} \times \frac{1\ \cancel{mol}\ \cancel{O_2}}{2\ \cancel{mol}\ \cancel{H_2O}} \times \frac{6.02 \times 10^{23}\text{ molecules } O_2}{1\ \cancel{mol}\ \cancel{O_2}}$$

$$N_{O_2} = 4.18 \times 10^{23}\text{ molecules}$$

In this reaction, 4.18×10^{23} molecules of oxygen would be produced.

PRACTICE

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Understanding Concepts

7. The fundamental test for a scientific concept is its ability to predict.
8. The reaction equation coefficients show the ratio of substances in moles, so measurements must be changed to amounts before the ratio can be applied.
9. (a) The mole ratio $CO_2 : C_8H_{18}$ (from the equation) is 16 : 2.
   (b) $2\ C_8H_{18(g)} + 25\ O_{2(g)} \rightarrow 16\ CO_{2(g)} + 18\ H_2O_{(g)}$
   22.8 g $\quad$ m
   114.26 g/mol $\quad$ 44.01 g/mol

$$n_{C_8H_{18}} = 22.8\ \cancel{g} \times \frac{1\text{ mol}}{114.26\ \cancel{g}}$$

$$n_{C_8H_{18}} = 0.200\text{ mol}$$

$$n_{CO_2} = 0.200\text{ mol} \times \frac{16}{2}$$

$$n_{CO_2} = 1.60\text{ mol}$$

$$m_{CO_2} = 1.60\ \cancel{mol} \times \frac{44.01\text{ g}}{1\ \cancel{mol}}$$

$$m_{CO_2} = 70.3\text{ g}$$

or

$$m_{CO_2} = 22.8\ \cancel{g}\ \cancel{C_8H_{18}} \times \frac{1\ \cancel{mol}\ \cancel{C_8H_{18}}}{114.26\ \cancel{g}\ \cancel{C_8H_{18}}} \times \frac{16\ \cancel{mol}\ \cancel{CO_2}}{2\ \cancel{mol}\ \cancel{C_8H_{18}}} \times \frac{44.01\text{ g } CO_2}{1\ \cancel{mol}\ \cancel{CO_2}}$$

$$m_{CO_2} = 70.3\text{ g}$$

The mass of carbon dioxide produced will be 70.3 g.

   (c) The mole ratio $O_2 : C_8H_{18}$ (from the equation) is 25 : 2.

(d)

$$\begin{array}{lllllll} 2\,C_8H_{18(g)} & + & 25\,O_{2(g)} & \rightarrow & 16\,CO_{2(g)} & + & 18\,H_2O_{(g)} \\ 22.8\text{ g} & & m & & & & \\ 114.26\text{ g/mol} & & 32.00\text{ g/mol} & & & & \end{array}$$

$$\begin{aligned} n_{C_8H_{18}} &= 22.8\,\cancel{g} \times \frac{1\text{ mol}}{114.26\,\cancel{g}} \\ n_{C_8H_{18}} &= 0.200\text{ mol} \\ n_{O_2} &= 0.200\text{ mol} \times \frac{25}{2} \\ n_{O_2} &= 2.49\text{ mol} \\ m_{O_2} &= 2.49\,\cancel{mol} \times \frac{32.00\text{ g}}{1\,\cancel{mol}} \\ m_{O_2} &= 79.8\text{ g} \end{aligned}$$

or

$$\begin{aligned} m_{O_2} &= 22.8\,\cancel{g}\,\cancel{C_8H_{18}} \times \frac{1\,\cancel{mol}\,\cancel{C_8H_{18}}}{114.26\,\cancel{g}\,\cancel{C_8H_{18}}} \times \frac{25\,\cancel{mol}\,\cancel{O_2}}{2\,\cancel{mol}\,\cancel{C_8H_{18}}} \times \frac{32.00\text{ g }O_2}{1\,\cancel{mol}\,\cancel{O_2}} \\ m_{O_2} &= 79.8\text{ g} \end{aligned}$$

The mass of oxygen consumed will be 79.8 g.

(e) If oxygen is the limiting reagent, some carbon will not react completely to $CO_{2(g)}$, but instead will react incompletely to form $CO_{(g)}$, which is very toxic.

10.

$$\begin{array}{l} TiO_{2(s)} + 2\,Cl_{2(g)} + 2\,C_{(s)} \rightarrow TiCl_{4(l)} + 2\,CO_{(g)} \\ 1.00\text{ kg} \\ 79.88\text{ g/mol} \end{array}$$

$$\begin{array}{lllllll} TiCl_{4(l)} & + & 2\,Mg_{(s)} & \rightarrow & Ti_{(s)} & + & 2\,MgCl_{2(s)} \\ & & & & m & & \\ & & & & 47.88\text{ g/mol} & & \end{array}$$

Note: This question requires the students to see that the mole ratio $TiCl_4 : TiO_2$ from the first equation can be combined with the mole ratio $Ti : TiCl_4$ from the second equation.

$$\begin{aligned} n_{TiO_2} &= 1.00\text{ k}\cancel{g} \times \frac{1\text{ mol}}{79.88\,\cancel{g}} \\ n_{TiO_2} &= 0.0125\text{ kmol} \\ n_{TiCl_4} &= 0.125\text{ kmol} \times \frac{1}{1} && \text{(mole ratio } TiCl_4 : TiO_2 \text{ is } 1 : 1 \text{ — step 1)} \\ n_{TiCl_4} &= 0.125\text{ kmol} \\ n_{Ti} &= 0.125\text{ kmol} \times \frac{1}{1} && \text{(mole ratio } Ti : TiCl_4 \text{ is } 1 : 1 \text{ — step 2)} \\ n_{Ti} &= 0.125\text{ kmol} \\ m_{Ti} &= 0.125\text{ k}\cancel{mol} \times \frac{47.88\text{ g}}{1\,\cancel{mol}} \\ m_{Ti} &= 0.599\text{ kg or 599 g} \end{aligned}$$

or

$$\begin{aligned} m_{Ti} &= 1.00\text{ k}\cancel{g}\,\cancel{TiO_2} \times \frac{1\,\cancel{mol}\,\cancel{TiO_2}}{79.88\,\cancel{g}\,\cancel{TiO_2}} \times \frac{1\,\cancel{mol}\,\cancel{TiCl_4}}{1\,\cancel{mol}\,\cancel{TiO_2}} \times \frac{1\,\cancel{mol}\,\cancel{Ti}}{1\,\cancel{mol}\,\cancel{TiCl_4}} \times \frac{47.88\text{ g Ti}}{1\,\cancel{mol}\,\cancel{Ti}} \\ m_{Ti} &= 0.599\text{ kg or 599 g} \end{aligned}$$

The (maximum) mass of titanium produced would be 599 g.

SECTION 5.4 QUESTIONS

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Understanding Concepts

1. Reaction equations read in amounts, not masses, so combining reagents by mass according to equation values will not work.
2. (a)

$$\begin{array}{lllllll} Fe_2O_{3(s)} & + & 3\,H_{2(g)} & \rightarrow & 2\,Fe_{(s)} & + & 3\,H_2O_{(g)} \\ 500\text{ kg} & & & & m & & \\ 159.70\text{ g/mol} & & & & 55.85\text{ g/mol} & & \end{array}$$

$$\begin{aligned} n_{Fe_2O_3} &= 500\text{ k}\cancel{\text{g}} \times \frac{1\text{ mol}}{159.70\ \cancel{\text{g}}} \\ n_{Fe_2O_3} &= 3.13\text{ kmol} \\ n_{Fe} &= 3.13\text{ kmol} \times \frac{2}{1} \\ n_{Fe} &= 6.26\text{ kmol} \\ m_{Fe} &= 6.26\text{ k}\cancel{\text{mol}} \times \frac{55.85\text{ g}}{1\ \cancel{\text{mol}}} \\ m_{Fe} &= 350\text{ kg} \end{aligned}$$

or

$$\begin{aligned} m_{Fe} &= 500\text{ k}\cancel{\text{g}}\ \cancel{Fe_2O_3} \times \frac{1\ \cancel{\text{mol}}\ \cancel{Fe_2O_3}}{159.70\ \cancel{\text{g}}\ \cancel{Fe_2O_3}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{Fe}}{1\ \cancel{\text{mol}}\ \cancel{Fe_2O_3}} \times \frac{55.85\text{ g Fe}}{1\ \cancel{\text{mol}}\ \cancel{Fe}} \\ m_{Fe} &= 350\text{ kg} \end{aligned}$$

The mass of iron produced would be 350 kg.

(b)

$$\begin{array}{lllllll} Fe_2O_{3(s)} & + & 3\,H_{2(g)} & \rightarrow & 2\,Fe_{(s)} & + & 3\,H_2O_{(g)} \\ 1.0\text{ t} = 1.0\text{ Mg} & & m & & & & \\ 159.70\text{ g/mol} & & 2.02\text{ g/mol} & & & & \end{array}$$

$$\begin{aligned} n_{Fe_2O_3} &= 1.0\text{ M}\cancel{\text{g}} \times \frac{1\text{ mol}}{159.70\ \cancel{\text{g}}} \\ n_{Fe_2O_3} &= 0.0063\text{ Mmol} = 6.3\text{ kmol} \\ n_{H_2} &= 0.0063\text{ Mmol} \times \frac{3}{1} \\ n_{H_2} &= 0.019\text{ Mmol} \\ m_{H_2} &= 0.019\text{ M}\cancel{\text{mol}} \times \frac{2.02\text{ g}}{1\ \cancel{\text{mol}}} \\ m_{H_2} &= 0.038\text{ Mg} = 38\text{ kg} \end{aligned}$$

or

$$\begin{aligned} m_{H_2} &= 1.0\text{ M}\cancel{\text{g}}\ \cancel{Fe_2O_3} \times \frac{1\ \cancel{\text{mol}}\ \cancel{Fe_2O_3}}{159.70\ \cancel{\text{g}}\ \cancel{Fe_2O_3}} \times \frac{3\ \cancel{\text{mol}}\ \cancel{H_2}}{1\ \cancel{\text{mol}}\ \cancel{Fe_2O_3}} \times \frac{2.02\text{ g }H_2}{1\ \cancel{\text{mol}}\ \cancel{H_2}} \\ m_{H_2} &= 0.038\text{ Mg} = 38\text{ kg} \end{aligned}$$

The mass of hydrogen required would be 38 kg.

(c)

$$\begin{array}{lllllll} Fe_2O_{3(s)} & + & 3\,H_{2(g)} & \rightarrow & 2\,Fe_{(s)} & + & 3\,H_2O_{(g)} \\ m & & & & & & 220\text{ kg} \\ 159.70\text{ g/mol} & & & & & & 18.02\text{ g/mol} \end{array}$$

$$\begin{aligned} n_{H_2O} &= 220\text{ k}\cancel{\text{g}} \times \frac{1\text{ mol}}{18.02\ \cancel{\text{g}}} \\ n_{H_2O} &= 12.2\text{ kmol} \\ n_{Fe_2O_3} &= 12.2\text{ kmol} \times \frac{1}{3} \\ n_{Fe_2O_3} &= 4.07\text{ kmol} \\ m_{Fe_2O_3} &= 4.07\text{ k}\cancel{\text{mol}} \times \frac{159.70\text{ g}}{1\ \cancel{\text{mol}}} \end{aligned}$$

$$m_{Fe_2O_3} = 650 \text{ kg}$$

or

$$m_{Fe_2O_3} = 220 \text{ k}\cancel{\text{g}}\ \cancel{H_2O} \times \frac{1 \cancel{\text{mol}}\ \cancel{H_2O}}{18.02 \cancel{\text{g}}\ \cancel{H_2O}} \times \frac{1 \cancel{\text{mol}}\ \cancel{Fe_2O_3}}{3 \cancel{\text{mol}}\ \cancel{H_2O}} \times \frac{159.70 \text{ g } Fe_2O_3}{1 \cancel{\text{mol}}\ \cancel{Fe_2O_3}}$$

$$m_{Fe_2O_3} = 650 \text{ kg}$$

The mass of iron(III) oxide consumed would be 650 kg.

3. (a) $2\ C_6H_{12(l)} + 5\ O_{2(g)} \rightarrow 2\ C_6H_{10}O_{4(s)} + 2\ H_2O_{(g)}$

m		280 kg
84.18 g/mol		146.16 g/mol

$$n_{C_6H_{10}O_4} = 280 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{146.16 \cancel{\text{g}}}$$

$$n_{C_6H_{10}O_4} = 1.92 \text{ kmol}$$

$$n_{C_6H_{12}} = 1.92 \text{ kmol} \times \frac{2}{2}$$

$$n_{C_6H_{12}} = 1.92 \text{ kmol}$$

$$m_{C_6H_{12}} = 1.92 \text{ k}\cancel{\text{mol}} \times \frac{84.18 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{C_6H_{12}} = 161 \text{ kg}$$

or

$$m_{C_6H_{12}} = 280 \text{ k}\cancel{\text{g}}\ \cancel{C_6H_{10}O_4} \times \frac{1 \cancel{\text{mol}}\ \cancel{C_6H_{10}O_4}}{146.16 \cancel{\text{g}}\ \cancel{C_6H_{10}O_4}} \times \frac{2 \cancel{\text{mol}}\ \cancel{C_6H_{12}}}{2 \cancel{\text{mol}}\ \cancel{C_6H_{10}O_4}} \times \frac{84.18 \text{ g } C_6H_{12}}{1 \cancel{\text{mol}}\ \cancel{C_6H_{12}}}$$

$$m_{C_6H_{12}} = 161 \text{ kg}$$

The mass of cyclohexane required is 161 kg.

(b) $2\ C_6H_{12(l)} + 5\ O_{2(g)} \rightarrow 2\ C_6H_{10}O_{4(s)} + 2\ H_2O_{(g)}$

125 kg	m
84.18 g/mol	32.00 g/mol

$$n_{C_6H_{12}} = 125 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{84.18 \cancel{\text{g}}}$$

$$n_{C_6H_{12}} = 1.48 \text{ kmol}$$

$$n_{O_2} = 1.48 \text{ kmol} \times \frac{5}{2}$$

$$n_{O_2} = 3.71 \text{ kmol}$$

$$m_{O_2} = 3.71 \text{ k}\cancel{\text{mol}} \times \frac{32.00 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{O_2} = 119 \text{ kg}$$

or

$$m_{O_2} = 125 \text{ k}\cancel{\text{g}}\ \cancel{C_6H_{12}} \times \frac{1 \cancel{\text{mol}}\ \cancel{C_6H_{12}}}{84.18 \cancel{\text{g}}\ \cancel{C_6H_{12}}} \times \frac{5 \cancel{\text{mol}}\ \cancel{O_2}}{2 \cancel{\text{mol}}\ \cancel{C_6H_{12}}} \times \frac{32.00 \text{ g } O_2}{1 \cancel{\text{mol}}\ \cancel{O_2}}$$

$$m_{O_2} = 119 \text{ kg}$$

The mass of oxygen required is 119 kg.

(c) $2\ C_6H_{12(l)} + 5\ O_{2(g)} \rightarrow 2\ C_6H_{10}O_{4(s)} + 2\ H_2O_{(g)}$

m	200 g
84.18 g/mol	32.00 g/mol

$$n_{O_2} = 200 \cancel{\text{g}} \times \frac{1 \text{ mol}}{32.00 \cancel{\text{g}}}$$

$$n_{O_2} = 6.25 \text{ mol}$$

$$n_{C_6H_{12}} = 6.25 \text{ mol} \times \frac{2}{5}$$

$$n_{C_6H_{12}} = 2.50 \text{ mol}$$

$$m_{C_6H_{12}} = 2.50\ \cancel{\text{mol}} \times \frac{84.18\ \text{g}}{1\ \cancel{\text{mol}}}$$

$$m_{C_6H_{12}} = 210\ \text{g}$$

or

$$m_{C_6H_{12}} = 200\ \cancel{\text{g}}\ \cancel{O_2} \times \frac{1\ \cancel{\text{mol}}\ \cancel{O_2}}{32.00\ \cancel{\text{g}}\ \cancel{O_2}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{C_6H_{12}}}{5\ \cancel{\text{mol}}\ \cancel{O_2}} \times \frac{84.18\ \text{g}\ C_6H_{12}}{1\ \cancel{\text{mol}}\ \cancel{C_6H_{12}}}$$

$$m_{C_6H_{12}} = 210\ \text{g}$$

The maximum mass of cyclohexane that can be reacted is 210 g.

4. $$\begin{array}{lllll} 2\ Fe_{(s)} & + & O_{2(g)} & \rightarrow & 2\ FeO_{(s)} \\ 56.8\ \text{g} & & & & m \\ 55.85\ \text{g/mol} & & & & 71.85\ \text{g/mol} \end{array}$$

$$n_{Fe} = 56.8\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{55.85\ \cancel{\text{g}}}$$

$$n_{Fe} = 1.02\ \text{mol}$$

$$n_{FeO} = 1.02\ \text{mol} \times \frac{2}{2}$$

$$n_{FeO} = 1.02\ \text{mol}$$

$$m_{FeO} = 1.02\ \cancel{\text{mol}} \times \frac{71.85\ \text{g}}{1\ \cancel{\text{mol}}}$$

$$m_{FeO} = 73.1\ \text{g}$$

or

$$m_{FeO} = 56.8\ \cancel{\text{g}}\ \cancel{Fe} \times \frac{1\ \cancel{\text{mol}}\ \cancel{Fe}}{55.85\ \cancel{\text{g}}\ \cancel{Fe}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{FeO}}{2\ \cancel{\text{mol}}\ \cancel{Fe}} \times \frac{71.85\ \text{g FeO}}{1\ \cancel{\text{mol}}\ \cancel{FeO}}$$

$$m_{FeO} = 73.1\ \text{g}$$

The mass of iron(II) oxide that can be produced is 73.1 g.

Applying Inquiry Skills

5. (a) **Prediction**

From the balanced reaction equation, one mole of calcium ions produces one mole of solid calcium oxalate precipitate, so the amount of calcium ions in a sample will be the same as the amount of calcium oxalate precipitate that forms.

(b) **Experimental Design**

Excess sodium oxalate solution will be added to a measured sample (independent variable) of hard water. The precipitate formed will be dried and the mass measured (dependent variable). The stoichiometric method will be used to calculate an answer to the question.

(c) The mass of calcium oxalate precipitate will be divided by its molar mass, 128.10 g/mol, to determine the amount of precipitate. The amount of calcium ions is the same, since the mole ratio is 1 : 1.

(d) **Materials**

- hard-water sample
- sodium oxalate solution
- wash bottle with pure water
- two 100-mL graduated cylinders
- 250-mL beaker
- filtration apparatus
- filter paper
- centigram balance

(e) **Procedure**

1. Use a graduated cylinder to add 10.0 mL of hard water to a 250-mL beaker.
2. Use another graduated cylinder to add about 10 mL of sodium oxalate solution to the beaker.
3. Allow the precipitate to settle.
4. Add another 10-mL aliquot of sodium oxalate solution to the beaker, observing whether or not more precipitate forms as the added solution mixes with the clear upper portion of the solution in the beaker.
5. Repeat step 4 until no more precipitate forms.
6. Measure and record the mass of a piece of filter paper.
7. Filter, wash, and dry the precipitate.
8. Measure and record the mass of the filter paper plus dry precipitate.
9. Dispose of all materials as instructed.

Making Connections

6. (a) Raw materials, like aluminum oxide, are purchased according to the amount needed for reaction.
   (b) Products, like aluminum, are priced so that the amount produced will be profitable.
   (c) Pollutant amounts will be calculated and decisions on processes to control them will be made accordingly.
   (d) Amounts of all materials must be calculated to allow costing of things like packaging, disposal, and shipping.

5.5 CALCULATING LIMITING AND EXCESS REAGENTS

PRACTICE

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Understanding Concepts

1. (a)

$$\begin{array}{lllllll} 2\ CH_{4(g)} & + & 3\ O_{2(g)} & \rightarrow & 2\ CO_{(g)} & + & 4\ H_2O_{(g)} \\ m & & & & & & \\ 16.05\text{ g/mol} & & 3.0\text{ mol} & & & & \end{array}$$

$$n_{CH_4} = 3.0\text{ mol} \times \frac{2}{3}$$

$$n_{CH_4} = 2.0\text{ mol}$$

$$m_{CH_4} = 2.0\ \cancel{\text{mol}} \times \frac{16.05\text{ g}}{1\ \cancel{\text{mol}}}$$

$$m_{CH_4} = 32\text{ g}$$

or

$$m_{CH_4} = 3\ \cancel{\text{mol}}\ \cancel{O_2} \times \frac{2\ \cancel{\text{mol}}\ \cancel{CH_4}}{3\ \cancel{\text{mol}}\ \cancel{O_2}} \times \frac{16.05\text{ g }CH_4}{1\ \cancel{\text{mol}}\ \cancel{CH_4}}$$

$$m_{CH_4} = 32\text{ g}$$

The mass of methane that will react is 32 g.

(b)

$$\begin{array}{lllllll} CH_{4(g)} & + & 2\ O_{2(g)} & \rightarrow & CO_{2(g)} & + & 2\ H_2O_{(g)} \\ m & & & & & & \\ 16.05\text{ g/mol} & & 3.0\text{ mol} & & & & \end{array}$$

$$n_{CH_4} = 3.0\text{ mol} \times \frac{1}{2}$$

$$n_{CH_4} = 1.5\text{ mol}$$

$$m_{CH_4} = 1.5\ \cancel{\text{mol}} \times \frac{16.05\text{ g}}{1\ \cancel{\text{mol}}}$$

$$m_{CH_4} = 24\text{ g}$$

or

$$m_{CH_4} = 3\ \cancel{\text{mol}}\ \cancel{O_2} \times \frac{1\ \cancel{\text{mol}}\ \cancel{CH_4}}{2\ \cancel{\text{mol}}\ \cancel{O_2}} \times \frac{16.05\text{ g }CH_4}{1\ \cancel{\text{mol}}\ \cancel{CH_4}}$$

$$m_{CH_4} = 24\ \text{g}$$

The mass of methane that will react is 24 g.

(c) In a closed garage the oxygen in the air will be the limiting reagent.

2. $$\begin{array}{llll} 8\ Zn_{(s)} & + \ S_{8(s)} & \rightarrow & 8\ ZnS_{(s)} \\ 5.00\ \text{g} & m & & \\ 65.38\ \text{g/mol} & 256.48\ \text{g/mol} & & \end{array}$$

$$n_{Zn} = 5.00\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{65.38\ \cancel{\text{g}}}$$

$$n_{Zn} = 0.0765\ \text{mol}$$

$$n_{S_8} = 0.0765\ \text{mol} \times \frac{1}{8}$$

$$n_{S_8} = 0.00956\ \text{mol}$$

$$m_{S_8} = 0.00956\ \cancel{\text{mol}} \times \frac{256.48\ \text{g}}{1\ \cancel{\text{mol}}}$$

$$m_{S_8} = 2.45\ \text{g}$$

or

$$m_{S_8} = 5.00\ \cancel{\text{g}}\ \cancel{Zn} \times \frac{1\ \cancel{\text{mol}}\ \cancel{Zn}}{65.38\ \cancel{\text{g}}\ \cancel{Zn}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{S_8}}{8\ \cancel{\text{mol}}\ \cancel{Zn}} \times \frac{256.48\ \text{g}\ S_8}{1\ \cancel{\text{mol}}\ \cancel{S_8}}$$

$$m_{S_8} = 2.45\ \text{g}$$

excess m_{S_8} = 2.45 g × 110% = 2.70 g

The mass of sulfur, to be in reasonable excess, should be 2.70 g.

3. $$\begin{array}{llll} 2\ Na_{(s)} & + \ Cl_{2(g)} & \rightarrow & 2\ NaCl_{(s)} \\ 0.75\ \text{g} & m & & \\ 22.99\ \text{g/mol} & 70.90\ \text{g/mol} & & \end{array}$$

$$n_{Na} = 0.75\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{22.99\ \cancel{\text{g}}}$$

$$n_{Na} = 0.033\ \text{mol}$$

$$n_{Cl_2} = 0.033\ \text{mol} \times \frac{1}{2}$$

$$n_{Cl_2} = 0.016\ \text{mol}$$

$$m_{Cl_2} = 0.016\ \cancel{\text{mol}} \times \frac{70.90\ \text{g}}{1\ \cancel{\text{mol}}}$$

$$m_{Cl_2} = 1.2\ \text{g}$$

or

$$m_{Cl_2} = 0.75\ \cancel{\text{g}}\ \cancel{Na} \times \frac{1\ \cancel{\text{mol}}\ \cancel{Na}}{22.99\ \cancel{\text{g}}\ \cancel{Na}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{Cl_2}}{2\ \cancel{\text{mol}}\ \cancel{Na}} \times \frac{70.90\ \text{g}\ Cl_2}{1\ \cancel{\text{mol}}\ \cancel{Cl_2}}$$

$$m_{Cl_2} = 1.2\ \text{g}$$

excess m_{Cl_2} = 1.2 g × 110% = 1.3 g

The mass of chlorine, to be in reasonable excess, should be 1.3 g.

4. $$\begin{array}{llllll} Ca(OH)_{2(s)} & + & 2\ HCl_{(aq)} & \rightarrow & CaCl_{2(aq)} & +\ 2\ H_2O_{(l)} \\ m & & 2.17\ \text{g} & & & \\ 74.10\ \text{g/mol} & & 36.46\ \text{g/mol} & & & \end{array}$$

$$n_{HCl} = 2.17\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{36.46\ \cancel{\text{g}}}$$

$$n_{HCl} = 0.0595\ \text{mol}$$

$$n_{Ca(OH)_2} = 0.0595\ \text{mol} \times \frac{1}{2}$$

$$n_{Ca(OH)_2} = 0.0298\ \text{mol}$$

$$m_{Ca(OH)_2} = 0.0298\ \cancel{\text{mol}} \times \frac{74.10\ \text{g}}{1\ \cancel{\text{mol}}}$$

$$m_{\text{Ca(OH)}_2} = 2.21 \text{ g}$$

or

$$m_{\text{Ca(OH)}_2} = 2.17 \cancel{\text{g}}\ \cancel{\text{HCl}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{HCl}}}{36.46\ \cancel{\text{g}}\ \cancel{\text{HCl}}} \times \frac{1\ \cancel{\text{mol}}\ \text{Ca}\cancel{\text{(OH)}}_2}{2\ \cancel{\text{mol}}\ \cancel{\text{HCl}}} \times \frac{74.10 \text{ g Ca(OH)}_2}{1\ \cancel{\text{mol}}\ \text{Ca}\cancel{\text{(OH)}}_2}$$

$$m_{\text{Ca(OH)}_2} = 2.21 \text{ g}$$

$$\text{excess } m_{\text{Ca(OH)}_2} = 2.21 \text{ g} \times 110\% = 2.43 \text{ g}$$

The mass of calcium hydroxide, to be in reasonable excess, should be 2.43 g.

PRACTICE

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Understanding Concepts

5. Prediction cannot be made from the amount of reagent in excess because not all of the amount will react.
6. (a)

$$\begin{array}{lllllll} \text{Zn}_{(s)} & + & \text{CuSO}_{4(aq)} & \rightarrow & \text{Cu}_{(s)} & + & \text{ZnSO}_{4(aq)} \\ 0.42 \text{ mol} & & 0.22 \text{ mol} & & & & \end{array}$$

Since this reactant mole ratio is 1:1, it is obvious by inspection that zinc is in excess, by an amount of (0.42 – 0.22) mol = 0.20 mol.

(b)

$$\begin{array}{lllllll} \text{Cl}_{2(g)} & + & 2\ \text{NaI}_{(aq)} & \rightarrow & \text{I}_{2(s)} & + & 2\ \text{NaCl}_{(aq)} \\ 10 \text{ mmol} & & 10 \text{ mmol} & & & & \end{array}$$

Since this reactant mole ratio is 1:2, 10 mmol of $\text{NaI}_{(aq)}$ will require 10 mmol × 1/2 = 5.0 mmol of $\text{Cl}_{2(g)}$ for reaction. The $\text{Cl}_{2(g)}$ is in excess by an amount of (10 – 5.0) mmol = 5 mmol.

(c)

$$\begin{array}{lllllll} \text{AlCl}_{3(aq)} & + & 3\ \text{NaOH}_{(aq)} & \rightarrow & \text{Al(OH)}_{3(s)} & + & 3\ \text{NaCl}_{(aq)} \\ 20 \text{ g} & & 19 \text{ g} & & & & \\ 133.33 \text{ g/mol} & & 40.00 \text{ g/mol} & & & & \end{array}$$

$$n_{\text{AlCl}_3} = 20\ \cancel{\text{g}} \times \frac{1 \text{ mol}}{133.33\ \cancel{\text{g}}}$$

$$n_{\text{AlCl}_3} = 0.150 \text{ mol}$$

$$n_{\text{NaOH}} = 19\ \cancel{\text{g}} \times \frac{1 \text{ mol}}{40.00\ \cancel{\text{g}}}$$

$$n_{\text{NaOH}} = 0.475 \text{ mol}$$

Since this reactant mole ratio is 1:3, 0.150 mol of $\text{AlCl}_{3(aq)}$ will require 0.150 mol × 3/1 = 0.450 mol of $\text{NaOH}_{(aq)}$ for reaction.

The $\text{NaOH}_{(aq)}$ is in excess, by an amount of (0.475 − 0.450) mol = 0.025 mol, or 25 mmol.

7. (a)

$$\begin{array}{lllll} 8\ \text{Zn}_{(s)} & + & \text{S}_{8(s)} & \rightarrow & 8\ \text{ZnS}_{(s)} \\ 5.00 \text{ g} & & 3.00 \text{ g} & & \\ 65.38 \text{ g/mol} & & 256.48 \text{ g/mol} & & \end{array}$$

$$n_{\text{Zn}} = 5.00\ \cancel{\text{g}} \times \frac{1 \text{ mol}}{65.38\ \cancel{\text{g}}}$$

$$n_{\text{Zn}} = 0.0765 \text{ mol}$$

$$n_{\text{S}_8} = 3.00\ \cancel{\text{g}} \times \frac{1 \text{ mol}}{256.48\ \cancel{\text{g}}}$$

$$n_{\text{S}_8} = 0.0117 \text{ mol}$$

Since this reactant mole ratio is 8:1, 0.0765 mol of $\text{Zn}_{(s)}$ will require 0.0765 mol × 1/8 = 0.00956 mol of $\text{S}_{8(s)}$ for reaction. The $\text{S}_{8(s)}$ is in excess; so the $\text{Zn}_{(s)}$ is the limiting reagent.

(b)

$$\begin{array}{lllll} 8\ \text{Zn}_{(s)} & + & \text{S}_{8(s)} & \rightarrow & 8\ \text{ZnS}_{(s)} \\ 5.00 \text{ g} & & & & m \\ 65.38 \text{ g/mol} & & & & 97.44 \text{ g/mol} \end{array}$$

$$\begin{aligned} n_{\text{Zn}} &= 5.00\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{65.38\ \cancel{\text{g}}} \\ n_{\text{Zn}} &= 0.0765\ \text{mol} \\ n_{\text{ZnS}} &= 0.0765\ \text{mol} \times \frac{8}{8} \\ n_{\text{ZnS}} &= 0.0765\ \text{mol} \\ m_{\text{ZnS}} &= 0.0765\ \cancel{\text{mol}} \times \frac{97.44\ \text{g}}{1\ \cancel{\text{mol}}} \\ m_{\text{ZnS}} &= 7.45\ \text{g} \end{aligned}$$

or

$$\begin{aligned} m_{\text{ZnS}} &= 5.00\ \cancel{\text{g}}\ \cancel{\text{Zn}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{Zn}}}{65.38\ \cancel{\text{g}}\ \cancel{\text{Zn}}} \times \frac{8\ \cancel{\text{mol}}\ \cancel{\text{S}_8}}{8\ \cancel{\text{mol}}\ \cancel{\text{Zn}}} \times \frac{97.44\ \text{g S}_8}{1\ \cancel{\text{mol}}\ \cancel{\text{S}_8}} \\ m_{\text{ZnS}} &= 7.45\ \text{g} \end{aligned}$$

The mass of zinc sulfide produced would be 7.45 g.

8. (a)
$$\begin{array}{lllllll} C_3H_{8(g)} & + & 5\ O_{2(g)} & \rightarrow & 3\ CO_{2(g)} & + & 4\ H_2O_{(g)} \\ 100.7\ \text{g} & & 367.4\ \text{g} & & & & \\ 44.11\ \text{g/mol} & & 32.00\ \text{g/mol} & & & & \end{array}$$

$$\begin{aligned} n_{C_3H_8} &= 100.7\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{44.11\ \cancel{\text{g}}} \\ n_{C_3H_8} &= 2.28\ \text{mol} \\ n_{O_2} &= 367.4\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{32.00\ \cancel{\text{g}}} \\ n_{O_2} &= 11.5\ \text{mol} \end{aligned}$$

Since this reactant mole ratio is 1:5, 2.28 mol of $C_3H_{8(g)}$ will require 2.28 mol × 5/1 = 11.4 mol of $O_{2(g)}$ for reaction. The $O_{2(g)}$ is in excess; so the $C_3H_{8(g)}$ is the limiting reagent.

(b)
$$\begin{array}{lllllll} C_3H_{8(g)} & + & 5\ O_{2(g)} & \rightarrow & 3\ CO_{2(g)} & + & 4\ H_2O_{(g)} \\ 100.7\ \text{g} & & & & & & m \\ 44.11\ \text{g/mol} & & & & & & 18.02\ \text{g/mol} \end{array}$$

$$\begin{aligned} n_{C_3H_8} &= 100.7\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{44.11\ \cancel{\text{g}}} \\ n_{C_3H_8} &= 2.283\ \text{mol} \\ n_{H_2O} &= 2.283\ \text{mol} \times \frac{4}{1} \\ n_{H_2O} &= 9.132\ \text{mol} \\ m_{H_2O} &= 9.132\ \cancel{\text{mol}} \times \frac{18.02\ \text{g}}{1\ \cancel{\text{mol}}} \\ m_{H_2O} &= 164.6\ \text{g} \end{aligned}$$

or

$$\begin{aligned} m_{H_2O} &= 100.7\ \cancel{\text{g}}\ \cancel{C_3H_8} \times \frac{1\ \cancel{\text{mol}}\ \cancel{C_3H_8}}{44.11\ \cancel{\text{g}}\ \cancel{C_3H_8}} \times \frac{4\ \cancel{\text{mol}}\ \cancel{H_2O}}{1\ \cancel{\text{mol}}\ \cancel{C_3H_8}} \times \frac{18.02\ \text{g}\ H_2O}{1\ \cancel{\text{mol}}\ \cancel{H_2O}} \\ m_{H_2O} &= 164.6\ \text{g} \end{aligned}$$

The mass of water formed is 164.6 g.

9. (a)
$$\begin{array}{lllll} 2\ SO_{2(g)} & + & O_{2(g)} & \rightarrow & 2\ SO_{3(g)} \\ 4.55\ \text{kg} & & 2.88\ \text{kg} & & \\ 64.06\ \text{g/mol} & & 32.00\ \text{g/mol} & & \end{array}$$

$$\begin{aligned} n_{SO_2} &= 4.55\ \text{k}\cancel{\text{g}} \times \frac{1\ \text{mol}}{64.06\ \cancel{\text{g}}} \\ n_{SO_2} &= 0.0710\ \text{kmol} \\ n_{O_2} &= 2.88\ \text{k}\cancel{\text{g}} \times \frac{1\ \text{mol}}{32.00\ \cancel{\text{g}}} \end{aligned}$$

$n_{O_2} = 0.0900 \text{ kmol}$

Since this reactant mole ratio is 2:1, 0.0710 kmol of $SO_{2(g)}$ will require 0.0710 kmol × 1/2 = 0.0355 kmol of $O_{2(g)}$ for reaction. The $O_{2(g)}$ is in excess; so the $SO_{2(g)}$ is the limiting reagent.

(b)
$$\begin{array}{lllll} 2\,SO_{2(g)} & + & O_{2(g)} & \rightarrow & 2\,SO_{3(g)} \\ 4.55\text{ kg} & & & & m \\ 64.06\text{ g/mol} & & & & 80.06\text{ g/mol} \end{array}$$

$$\begin{aligned} n_{SO_2} &= 4.55\text{ k}\cancel{\text{g}} \times \frac{1\text{ mol}}{64.06\ \cancel{\text{g}}} \\ n_{SO_2} &= 0.0710\text{ kmol} \\ n_{SO_3} &= 0.0710\text{ kmol} \times \frac{2}{2} \\ n_{SO_3} &= 0.0710\text{ kmol} \\ m_{SO_3} &= 0.0710\text{ k}\cancel{\text{mol}} \times \frac{80.06\text{ g}}{1\ \cancel{\text{mol}}} \\ m_{SO_3} &= 5.69\text{ kg} \end{aligned}$$

or

$$\begin{aligned} m_{SO_3} &= 4.55\text{ k}\cancel{\text{g}}\ \cancel{SO_2} \times \frac{1\ \cancel{\text{mol}}\ \cancel{SO_2}}{64.06\ \cancel{\text{g}}\ \cancel{SO_2}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{SO_3}}{2\ \cancel{\text{mol}}\ \cancel{SO_2}} \times \frac{80.06\text{ g }SO_3}{1\ \cancel{\text{mol}}\ \cancel{SO_3}} \\ m_{SO_3} &= 5.69\text{ kg} \end{aligned}$$

The mass of sulfur trioxide produced is 5.69 kg.

10. (a)
$$\begin{array}{lllllll} Fe_2O_{3(s)} & + & 3\,CO_{(g)} & \rightarrow & 2\,Fe_{(s)} & + & 3\,CO_{2(g)} \\ 74.2\text{ kg} & & 40.3\text{ kg} & & & & \\ 159.70\text{ g/mol} & & 28.01\text{ g/mol} & & & & \end{array}$$

$$\begin{aligned} n_{Fe_2O_3} &= 74.2\text{ k}\cancel{\text{g}} \times \frac{1\text{ mol}}{159.70\ \cancel{\text{g}}} \\ n_{Fe_2O_3} &= 0.465\text{ kmol} \\ n_{CO} &= 40.3\text{ k}\cancel{\text{g}} \times \frac{1\text{ mol}}{28.01\ \cancel{\text{g}}} \\ n_{CO} &= 1.44\text{ kmol} \end{aligned}$$

Since this reactant mole ratio is 1:3, 0.465 kmol of $Fe_2O_{3(s)}$ will require 0.465 kmol × 3/1 = 1.39 kmol of $CO_{(g)}$ for reaction. The $CO_{(g)}$ is in excess; so the $Fe_2O_{3(s)}$ is the limiting reagent.

(b)
$$\begin{array}{lllllll} Fe_2O_{3(s)} & + & 3\,CO_{(g)} & \rightarrow & 2\,Fe_{(s)} & + & 3\,CO_{2(g)} \\ 74.2\text{ kg} & & & & m & & \\ 159.70\text{ g/mol} & & & & 55.85\text{ g/mol} & & \end{array}$$

$$\begin{aligned} n_{Fe_2O_3} &= 74.2\text{ k}\cancel{\text{g}} \times \frac{1\text{ mol}}{159.70\ \cancel{\text{g}}} \\ n_{Fe_2O_3} &= 0.465\text{ kmol} \\ n_{Fe} &= 0.465\text{ kmol} \times \frac{2}{1} \\ n_{Fe} &= 0.929\text{ kmol} \\ m_{Fe} &= 0.929\text{ k}\cancel{\text{mol}} \times \frac{55.85\text{ g}}{1\ \cancel{\text{mol}}} \\ m_{Fe} &= 51.9\text{ kg} \end{aligned}$$

or

$$\begin{aligned} m_{Fe} &= 74.2\text{ k}\cancel{\text{g}}\ \cancel{Fe_2O_3} \times \frac{1\ \cancel{\text{mol}}\ \cancel{Fe_2O_3}}{159.70\ \cancel{\text{g}}\ \cancel{Fe_2O_3}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{Fe}}{1\ \cancel{\text{mol}}\ \cancel{Fe_2O_3}} \times \frac{55.85\text{ g Fe}}{1\ \cancel{\text{mol}}\ \cancel{Fe}} \\ m_{Fe} &= 51.9\text{ kg} \end{aligned}$$

The mass of iron produced would be 51.9 kg.

Applying Inquiry Skills

11. **Experimental Design**

A solid reaction product can be removed (by filtration, for instance) from the reaction system. If some more of the (presumed) excess reagent is added, and no reaction occurs, then the limiting reagent is completely reacted and the other reagent was in excess.

PRACTICE

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Applying Inquiry Skills

12. (a) If aluminum is the limiting reagent, the silver metal solid will have completely disappeared when the reaction stops.
    (b) If copper(II) sulfate is the limiting reagent, the silver metal solid will not have completely disappeared when the reaction stops.
13. (a) If magnesium is the limiting reagent, the silver metal solid will have completely disappeared when the reaction stops.
    (b) If hydrochloric acid is the limiting reagent, the silver metal solid will not have completely disappeared when the reaction stops.

SECTION 5.5 QUESTIONS

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Understanding Concepts

1. The limiting reagent is determined by the reaction mole ratio; so the mass may actually be much greater than the excess reagent, as long as the amount is such that it is completely reacted.
2. The reaction only occurs until the limiting reagent is consumed, so the amount of the limiting reagent determines all other amounts involved in the reaction.
3. One (or more) reactants must be in excess to ensure that the limiting reagent will be completely reacted.
4. (a) $Zn_{(s)}$ + $2\ HCl_{(aq)}$ → $H_{2(g)}$ + $ZnCl_{2(aq)}$

   0.35 mol   0.60 mol

   Since this reactant mole ratio is 1:2, 0.60 mol of $HCl_{(aq)}$ will require 0.60 mol × 1/2 = 0.30 mol of $Zn_{(s)}$ for reaction. The $Zn_{(s)}$ is in excess; so the $HCl_{(aq)}$ is the limiting reagent, and will be completely consumed.

   (b) The $Zn_{(s)}$ is in excess, by an amount of (0.35 − 0.30) mol = 0.05 mol.

   excess m_{Zn} = 0.05 mol × 65.38 g/1 mol = 3 g

   The mass of zinc remaining after the reaction ends will be 3 g.
5. (a) $2\ KBr_{(aq)}$ + $Pb(NO_3)_{2(aq)}$ → $2\ KNO_{3(aq)}$ + $PbBr_{2(s)}$

   m 3.50 g

   119.00 g/mol   331.22 g/mol

$$n_{Pb(NO_3)_2} = 3.50\ \cancel{g} \times \frac{1\ mol}{331.22\ \cancel{g}}$$

$$n_{Pb(NO_3)_2} = 0.0106\ mol$$

$$n_{KBr} = 0.0106\ mol \times \frac{1}{2}$$

$$n_{KBr} = 0.00528\ mol$$

$$m_{KBr} = 0.00528\ \cancel{mol} \times \frac{119.00\ g}{1\ \cancel{mol}}$$

$$m_{KBr} = 0.629\ g$$

or

$$m_{KBr} = 3.50\ \cancel{g}\ Pb(\cancel{NO_3})_2 \times \frac{1\ \cancel{mol}\ Pb(\cancel{NO_3})_2}{331.22\ \cancel{g}\ Pb(\cancel{NO_3})_2} \times \frac{1\ \cancel{mol}\ \cancel{KBr}}{2\ \cancel{mol}\ Pb(\cancel{NO_3})_2} \times \frac{119.00\ g\ KBr}{1\ \cancel{mol}\ \cancel{KBr}}$$

$$m_{KBr} = 0.629\ g$$

excess $m_{\text{KBr}} = 0.629\text{ g} \times 110\% = 0.692\text{ g}$

The mass of potassium bromide, to be in reasonable excess, should be 692 mg.

(b)
$$\begin{array}{lllll}
2\ \text{KBr}_{(aq)} & + \quad \text{Pb(NO}_3)_{2(aq)} & \rightarrow\ 2\ \text{KNO}_{3(aq)} & + & \text{PbBr}_{2(s)} \\
 & \quad 3.50\text{ g} & \quad m & & \\
 & \quad 331.22\text{ g/mol} & \quad 367.00\text{ g/mol} & &
\end{array}$$

$$\begin{aligned}
n_{\text{Pb(NO}_3)_2} &= 3.50\ \cancel{\text{g}} \times \frac{1\text{ mol}}{331.22\ \cancel{\text{g}}} \\
n_{\text{Pb(NO}_3)_2} &= 0.0106\text{ mol} \\
n_{\text{PbBr}_2} &= 0.0106\text{ mol} \times \frac{1}{1} \\
n_{\text{PbBr}_2} &= 0.0106\text{ mol} \\
m_{\text{PbBr}_2} &= 0.0106\ \cancel{\text{mol}} \times \frac{119.00\text{ g}}{1\ \cancel{\text{mol}}} \\
m_{\text{PbBr}_2} &= 0.629\text{ g}
\end{aligned}$$

or

$$\begin{aligned}
m_{\text{PbBr}_2} &= 3.50\ \cancel{\text{g}}\ \cancel{\text{Pb(NO}_3)_2} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{Pb(NO}_3)_2}}{331.22\ \cancel{\text{g}}\ \cancel{\text{Pb(NO}_3)_2}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{PbBr}_2}}{1\ \cancel{\text{mol}}\ \cancel{\text{Pb(NO}_3)_2}} \times \frac{119.00\text{ g PbBr}_2}{1\ \cancel{\text{mol}}\ \cancel{\text{PbBr}_2}} \\
m_{\text{PbBr}_2} &= 0.629\text{ g}
\end{aligned}$$

The mass of lead(II) bromide produced would be 0.629 g.

6. (a)
$$\begin{array}{lllll}
\text{Cu}_{(s)} & + \quad 2\ \text{AgNO}_{3(aq)} & \rightarrow\ 2\ \text{Ag}_{(s)} & + & \text{Cu(NO}_3)_{2(aq)} \\
10.0\text{ g} & \quad 20.0\text{ g} & & & \\
63.55\text{ g/mol} & \quad 169.88\text{ g/mol} & & &
\end{array}$$

$$\begin{aligned}
n_{\text{Cu}} &= 10.0\ \cancel{\text{g}} \times \frac{1\text{ mol}}{63.55\ \cancel{\text{g}}} \\
n_{\text{Cu}} &= 0.157\text{ mol} \\
n_{\text{AgNO}_3} &= 20.0\ \cancel{\text{g}} \times \frac{1\text{ mol}}{169.88\ \cancel{\text{g}}} \\
n_{\text{AgNO}_3} &= 0.118\text{ mol}
\end{aligned}$$

Since this reactant mole ratio is 1:2, 0.118 mol of $\text{AgNO}_{3(aq)}$ will require 0.118 mol × 1/2 = 0.0589 mol of $\text{Cu}_{(s)}$ for reaction. The $\text{Cu}_{(s)}$ is in excess; so the $\text{AgNO}_{3(aq)}$ is the limiting reagent.

(b)
$$\begin{array}{lllll}
\text{Cu}_{(s)} & + \quad 2\ \text{AgNO}_{3(aq)} & \rightarrow & 2\ \text{Ag}_{(s)} & + \ \text{Cu(NO}_3)_{2(aq)} \\
 & \quad 20.0\text{ g} & & m & \\
 & \quad 169.88\text{ g/mol} & & 107.87\text{ g/mol} &
\end{array}$$

$$\begin{aligned}
n_{\text{AgNO}_3} &= 20.0\ \cancel{\text{g}} \times \frac{1\text{ mol}}{169.88\ \cancel{\text{g}}} \\
n_{\text{AgNO}_3} &= 0.118\text{ mol} \\
n_{\text{Ag}} &= 0.118\text{ mol} \times \frac{2}{2} \\
n_{\text{Ag}} &= 0.118\text{ mol} \\
m_{\text{Ag}} &= 0.118\ \cancel{\text{mol}} \times \frac{107.87\text{ g}}{1\ \cancel{\text{mol}}} \\
m_{\text{Ag}} &= 12.7\text{ g}
\end{aligned}$$

or

$$\begin{aligned}
m_{\text{Ag}} &= 20.0\ \cancel{\text{g}}\ \cancel{\text{AgNO}_3} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{AgNO}_3}}{169.88\ \cancel{\text{g}}\ \cancel{\text{AgNO}_3}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{\text{Ag}}}{2\ \cancel{\text{mol}}\ \cancel{\text{AgNO}_3}} \times \frac{107.87\text{ g Ag}}{1\ \cancel{\text{mol}}\ \cancel{\text{Ag}}} \\
m_{\text{Ag}} &= 12.7\text{ g}
\end{aligned}$$

The mass of silver crystals produced would be 12.7 g.

7. (a)

$$\begin{array}{lllllll}
FeCl_{3(aq)} & + & 3\ NaOH_{(aq)} & \rightarrow & Fe(OH)_{3(s)} & + & 3\ NaCl_{(aq)} \\
26.8\ g & & 21.5\ g & & & & \\
162.20\ g/mol & & 40.00\ g/mol & & & &
\end{array}$$

$$n_{NaOH} = 21.5\ \cancel{g} \times \frac{1\ mol}{40.00\ \cancel{g}}$$

$$n_{NaOH} = 0.538\ mol$$

$$n_{FeCl_3} = 26.8\ \cancel{g} \times \frac{1\ mol}{162.20\ \cancel{g}}$$

$$n_{FeCl_3} = 0.165\ mol$$

Since this reactant mole ratio is 1:3, 0.165 mol of $FeCl_{3(aq)}$ will require 0.165 mol × 3/1 = 0.496 mol of $NaOH_{(aq)}$ for reaction. The $NaOH_{(aq)}$ is in excess; so the $FeCl_{3(aq)}$ is the limiting reagent.

(b)

$$\begin{array}{lllllll}
FeCl_{3(aq)} & + & 3\ NaOH_{(aq)} & \rightarrow & Fe(OH)_{3(s)} & + & 3\ NaCl_{(aq)} \\
26.8\ g & & & & m & & m \\
162.20\ g/mol & & & & 106.88\ g/mol & & 58.44\ g/mol
\end{array}$$

$$n_{FeCl_3} = 26.8\ \cancel{g} \times \frac{1\ mol}{162.20\ \cancel{g}}$$

$$n_{FeCl_3} = 0.165\ mol$$

$$n_{Fe(OH)_3} = 0.165\ mol \times \frac{1}{1}$$

$$n_{Fe(OH)_3} = 0.165\ mol$$

$$m_{Fe(OH)_3} = 0.165\ \cancel{mol} \times \frac{106.88\ g}{1\ \cancel{mol}}$$

$$m_{Fe(OH)_3} = 17.7\ g$$

or

$$m_{Fe(OH)_3} = 26.8\ \cancel{g}\ \cancel{FeCl_3} \times \frac{1\ \cancel{mol}\ \cancel{FeCl_3}}{162.20\ \cancel{g}\ \cancel{FeCl_3}} \times \frac{1\ \cancel{mol}\ \cancel{Fe(OH)_3}}{1\ \cancel{mol}\ \cancel{FeCl_3}} \times \frac{106.88\ g\ Fe(OH)_3}{1\ \cancel{mol}\ \cancel{Fe(OH)_3}}$$

$$m_{Fe(OH)_3} = 17.7\ g$$

The mass of iron(III) hydroxide produced would be 17.7 g

and $$n_{NaCl} = 0.165\ mol \times \frac{3}{1}$$

$$n_{NaCl} = 0.496\ mol$$

$$m_{NaCl} = 0.496\ \cancel{mol} \times \frac{58.44\ g}{1\ \cancel{mol}}$$

$$m_{NaCl} = 29.0\ g$$

or

$$m_{NaCl} = 26.8\ \cancel{g}\ \cancel{FeCl_3} \times \frac{1\ \cancel{mol}\ \cancel{FeCl_3}}{162.20\ \cancel{g}\ \cancel{FeCl_3}} \times \frac{3\ \cancel{mol}\ \cancel{NaCl}}{1\ \cancel{mol}\ \cancel{FeCl_3}} \times \frac{58.44\ g\ NaCl}{1\ \cancel{mol}\ \cancel{NaCl}}$$

$$m_{NaCl} = 29.0\ g$$

The mass of sodium chloride produced would be 29.0 g.

Applying Inquiry Skills

8. Determining if enough excess reagent has been added is the same as determining if all of the limiting reagent has reacted. This can be done in any situation where a product can be removed from the reaction. For example, in a reaction of zinc and hydrochloric acid, where hydrogen bubbles escape, if more zinc is added and no bubbles form, then all of the hydrochloric acid must have reacted.

5.6 THE YIELD OF A CHEMICAL REACTION

PRACTICE

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Understanding Concepts

1. The quantity of product predicted by stoichiometric calculation is the theoretical yield. When the reaction is carried out, the measured quantity of product obtained is the actual yield.
2. An actual yield is a measured quantity, and normal measurement error as well as experimental error can result in this value being greater than the theoretical yield.
3. (a) $NaBr_{(aq)} + AgNO_{3(aq)} \rightarrow NaNO_{3(aq)} + AgBr_{(s)}$

(b)

$$\begin{array}{lllllll} NaBr_{(aq)} & + & AgNO_{3(aq)} & \rightarrow & NaNO_{3(aq)} & + & AgBr_{(s)} \\ & & 5.00\text{ g} & & & & m\ (5.03\text{ g actual}) \\ & & 169.88\text{ g/mol} & & & & 187.77\text{ g/mol} \end{array}$$

$$\begin{aligned} n_{AgNO_3} &= 5.00\ \cancel{g} \times \frac{1\text{ mol}}{169.88\ \cancel{g}} \\ n_{AgNO_3} &= 0.0294\text{ mol} \\ n_{AgBr} &= 0.0294\text{ mol} \times \frac{1}{1} \\ n_{AgBr} &= 0.0294\text{ mol} \\ m_{AgBr} &= 0.0294\ \cancel{mol} \times \frac{187.77\text{ g}}{1\ \cancel{mol}} \\ m_{AgBr} &= 5.53\text{ g} \end{aligned}$$

or

$$\begin{aligned} m_{AgBr} &= 5.00\ \cancel{g}\ \cancel{AgNO_3} \times \frac{1\ \cancel{mol}\ \cancel{AgNO_3}}{169.88\ \cancel{g}\ \cancel{AgNO_3}} \times \frac{1\ \cancel{mol}\ \cancel{AgBr}}{1\ \cancel{mol}\ \cancel{AgNO_3}} \times \frac{187.77\text{ g AgBr}}{1\ \cancel{mol}\ \cancel{AgBr}} \\ m_{AgBr} &= 5.53\text{ g} \end{aligned}$$

The mass of silver bromide produced should be 5.53 g.

(c) The mass of silver bromide actually produced is 5.03 g.

(d) $\%\text{ yield} = \dfrac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

$$\%\text{ yield} = \frac{5.03\ \cancel{g}}{5.53\ \cancel{g}} \times 100\% = 91.0\%$$

The percentage yield of silver bromide in this reaction is 91.0%.

4. (a)

$$\begin{array}{lllllll} 4\ FeS_{(s)} & + & 7\ O_{2(g)} & \rightarrow & 2\ Fe_2O_{3(s)} & + & 4\ SO_{2(g)} \\ 16.1\text{ g} & & 10.8\text{ g} & & & & \\ 87.91\text{ g/mol} & & 32.00\text{ g/mol} & & & & \end{array}$$

$$\begin{aligned} n_{FeS} &= 16.1\ \cancel{g} \times \frac{1\text{ mol}}{87.91\ \cancel{g}} \\ n_{FeS} &= 0.183\text{ mol} \\ n_{O_2} &= 10.8\ \cancel{g} \times \frac{1\text{ mol}}{32.00\ \cancel{g}} \\ n_{O_2} &= 0.338\text{ mol} \end{aligned}$$

Since this reactant mole ratio is 4:7, 0.183 mol of $FeS_{(s)}$ will require 0.183 mol × 7/4 = 0.320 mol of $O_{2(g)}$ for reaction. The $O_{2(g)}$ is in excess; so the $FeS_{(s)}$ is the limiting reagent.

(b)

$$\begin{array}{lllllll} 4\ FeS_{(s)} & + & 7\ O_{2(g)} & \rightarrow & 2\ Fe_2O_{3(s)} & + & 4\ SO_{2(g)} \\ 16.1\text{ g} & & & & m\ (14.1\text{ g actual}) & & \\ 87.91\text{ g/mol} & & & & 159.70\text{ g/mol} & & \end{array}$$

$$n_{FeS} = 16.1\ \cancel{g} \times \frac{1\text{ mol}}{87.91\ \cancel{g}}$$

$$n_{FeS} = 0.183 \text{ mol}$$

$$n_{Fe_2O_3} = 0.183 \text{ mol} \times \frac{2}{4}$$

$$n_{Fe_2O_3} = 0.0916 \text{ mol}$$

$$m_{Fe_2O_3} = 0.0916 \cancel{\text{mol}} \times \frac{159.70 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{Fe_2O_3} = 14.6 \text{ g}$$

or

$$m_{Fe_2O_3} = 16.1 \cancel{\text{g}} \cancel{\text{FeS}} \times \frac{1 \cancel{\text{mol}} \cancel{\text{FeS}}}{87.91 \cancel{\text{g}} \cancel{\text{FeS}}} \times \frac{2 \cancel{\text{mol}} \cancel{\text{Fe}_2\text{O}_3}}{4 \cancel{\text{mol}} \cancel{\text{FeS}}} \times \frac{159.70 \text{ g Fe}_2\text{O}_3}{1 \cancel{\text{mol}} \cancel{\text{Fe}_2\text{O}_3}}$$

$$m_{Fe_2O_3} = 14.6 \text{ g}$$

The theoretical yield of iron(III) oxide would be 14.6 g.

(c) $$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\% \text{ yield} = \frac{14.1 \cancel{\text{g}}}{14.6 \cancel{\text{g}}} \times 100\% = 96.6\%$$

The percentage yield of iron(III) oxide in this reaction is 96.6%.

5.

$Fe_2O_{3(s)}$	+	$3\ CO_{(g)}$	→	$2\ Fe_{(s)}$	+	$3\ CO_{2(g)}$
1000 kg				m (635 kg actual)		
159.70 g/mol				55.85 g/mol		

$$n_{Fe_2O_3} = 1000 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{159.70 \cancel{\text{g}}}$$

$$n_{Fe_2O_3} = 6.26 \text{ kmol}$$

$$n_{Fe} = 6.26 \text{ kmol} \times \frac{2}{1}$$

$$n_{Fe} = 12.5 \text{ kmol}$$

$$m_{Fe} = 12.5 \text{ k}\cancel{\text{mol}} \times \frac{55.85 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{Fe} = 699 \text{ kg}$$

or

$$m_{Fe} = 1000 \text{ k}\cancel{\text{g}} \cancel{\text{Fe}_2\text{O}_3} \times \frac{1 \cancel{\text{mol}} \cancel{\text{Fe}_2\text{O}_3}}{159.70 \cancel{\text{g}} \cancel{\text{Fe}_2\text{O}_3}} \times \frac{2 \cancel{\text{mol}} \cancel{\text{Fe}}}{1 \cancel{\text{mol}} \cancel{\text{Fe}_2\text{O}_3}} \times \frac{55.85 \text{ g Fe}}{1 \cancel{\text{mol}} \cancel{\text{Fe}}}$$

$$m_{Fe} = 699 \text{ kg}$$

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\% \text{ yield} = \frac{635 \cancel{\text{kg}}}{699 \cancel{\text{kg}}} \times 100\% = 90.8\%$$

The percentage yield of iron in this reaction is 90.8%.

6.

$C_7H_6O_{3(s)}$	+	$CH_3OH_{(l)}$	→	$C_8H_8O_{3(l)}$	+	$H_2O_{(l)}$
2.00 g				m (1.65 g actual)		
138.13 g/mol				152.16 g/mol		

$$n_{C_7H_6O_3} = 2.00 \cancel{\text{g}} \times \frac{1 \text{ mol}}{138.13 \cancel{\text{g}}}$$

$$n_{C_7H_6O_3} = 0.0145 \text{ mol}$$

$$n_{C_8H_8O_3} = 0.0145 \text{ mol} \times \frac{1}{1}$$

$$n_{C_8H_8O_3} = 0.0145 \text{ mol}$$

$$m_{C_8H_8O_3} = 0.0145 \cancel{\text{mol}} \times \frac{152.16 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{C_8H_8O_3} = 2.20 \text{ g}$$

or

$$m_{C_8H_8O_3} = 2.00\ \cancel{g}\ \cancel{C_7H_6O_3} \times \frac{1\ \cancel{mol}\ \cancel{C_7H_6O_3}}{138.13\ \cancel{g}\ \cancel{C_7H_6O_3}} \times \frac{1\ \cancel{mol}\ \cancel{C_8H_8O_3}}{1\ \cancel{mol}\ \cancel{C_7H_6O_3}} \times \frac{152.16\ g\ C_8H_8O_3}{1\ \cancel{mol}\ \cancel{C_8H_8O_3}}$$

$$m_{C_8H_8O_3} = 2.20\ g$$

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\%\ \text{yield} = \frac{1.65\ \cancel{g}}{2.20\ \cancel{g}} \times 100\% = 74.9\%.$$

The percentage yield of methyl salicylate in this reaction is 74.9%

Applying Inquiry Skills

7. The procedure listed is fatally flawed if the reaction produces any other product (besides the precipitate) that does not vaporize upon heating, because any such product will also be mixed with the precipitate in the evaporating dish. The normal way to efficiently recover a precipitate is to filter it using a piece of filter paper of known (measured) mass, wash and dry it, and measure the mass of the paper plus precipitate.

Making Connections

8. (a) Student research should indicate how large-scale industry practices and procedures result in a more efficient extraction of the red dye, carmine, from the bodies of female Dactylopus coccus insects (cochineal insects) than the original hand process of crushing the insects and simmering them in water to extract the dye. Since so many insects are needed to produce a reasonable amount (150 000 insects per kilogram of carmine), the product is costly and the process efficiency is, therefore, very important.

   (b) As the insects live on desert cactus plants, cochineal carmine can be produced in arid areas where no other profitable crop can be harvested. This means that in Peru a significantly profitable industry and source of income for the residents of desert areas depends on these tiny bugs.

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PRACTICE

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Understanding Concepts

9. Yield less than predicted in a reaction may be due to experimental error inherent in the procedure; to impurities in the reagents; to unwanted side reactions; and to reactions that are not quantitative — that do not “go to completion.”

10. (a)

$$\begin{array}{lllll} 2\ Cu_2O_{(s)} & + & Cu_2S_{(s)} & \rightarrow & 6\ Cu_{(s)}\ +\ SO_{2(g)} \\ 250\ kg & & 129\ kg & & \\ 143.10\ g/mol & & 159.16\ g/mol & & \end{array}$$

$$n_{Cu_2O} = 250\ k\cancel{g} \times \frac{1\ mol}{143.10\ \cancel{g}}$$

$$n_{Cu_2O} = 1.75\ kmol$$

$$n_{Cu_2S} = 129\ k\cancel{g} \times \frac{1\ mol}{159.16\ \cancel{g}}$$

$$n_{Cu_2S} = 0.811\ kmol$$

Since this reactant mole ratio is 2:1, 0.811 kmol of $Cu_2S_{(s)}$ will require 0.811 kmol × 2/1 = 1.62 kmol of $Cu_2O_{(s)}$ for reaction. The $Cu_2O_{(s)}$ is in excess; so the $Cu_2S_{(s)}$ is the limiting reagent.

(b)

$$\begin{array}{lllll} 2\ Cu_2O_{(s)} & + & Cu_2S_{(s)} & \rightarrow & 6\ Cu_{(s)}\ +\ SO_{2(g)} \\ & & 129\ kg & & m\ (285\ kg\ \text{actual}) \\ & & 159.16\ g/mol & & 63.55\ g/mol \end{array}$$

$$n_{Cu_2S} = 129\ k\cancel{g} \times \frac{1\ mol}{159.16\ \cancel{g}}$$

$$n_{Cu_2S} = 0.811\ kmol$$

$$
\begin{aligned}
n_{\text{Cu}} &= 0.811\ \text{kmol} \times \frac{6}{1} \\
n_{\text{Cu}} &= 4.86\ \text{kmol} \\
m_{\text{Cu}} &= 4.86\ \text{k}\cancel{\text{mol}} \times \frac{63.55\ \text{g}}{1\ \cancel{\text{mol}}} \\
m_{\text{Cu}} &= 309\ \text{kg}
\end{aligned}
$$

or

$$
\begin{aligned}
m_{\text{Cu}} &= 129\ \text{k}\cancel{\text{g}}\ \cancel{\text{Cu}_2\text{S}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{Cu}_2\text{S}}}{159.16\ \cancel{\text{g}}\ \cancel{\text{Cu}_2\text{S}}} \times \frac{6\ \cancel{\text{mol}}\ \cancel{\text{Cu}}}{1\ \cancel{\text{mol}}\ \cancel{\text{Cu}_2\text{S}}} \times \frac{63.55\ \text{g Cu}}{1\ \cancel{\text{mol}}\ \cancel{\text{Cu}}} \\
m_{\text{Cu}} &= 309\ \text{kg}
\end{aligned}
$$

The theoretical yield of copper would be 309 kg.

(c) $\%\ \text{yield} = \dfrac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

$$\%\ \text{yield} = \frac{285\ \cancel{\text{kg}}}{309\ \cancel{\text{kg}}} \times 100\% = 92.2\%$$

The percentage yield of copper in this reaction is 92.2%.

11. (a)

$C_{(s)}$	+	$2\ H_{2(g)}$	→	$CH_{4(g)}$
10.0 kg				*m* (4.20 kg actual)
12.01 g/mol				16.05 g/mol

$$
\begin{aligned}
n_{\text{C}} &= 10.0\ \text{k}\cancel{\text{g}} \times \frac{1\ \text{mol}}{12.01\ \cancel{\text{g}}} \\
n_{\text{C}} &= 0.833\ \text{kmol} \\
n_{\text{CH}_4} &= 0.833\ \text{kmol} \times \frac{1}{1} \\
n_{\text{CH}_4} &= 0.833\ \text{kmol} \\
m_{\text{CH}_4} &= 0.833\ \text{k}\cancel{\text{mol}} \times \frac{16.05\ \text{g}}{1\ \cancel{\text{mol}}} \\
m_{\text{CH}_4} &= 13.4\ \text{kg}
\end{aligned}
$$

or

$$
\begin{aligned}
m_{\text{CH}_4} &= 10.0\ \text{k}\cancel{\text{g}}\ \cancel{\text{C}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{C}}}{12.01\ \cancel{\text{g}}\ \cancel{\text{C}}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{CH}_4}}{1\ \cancel{\text{mol}}\ \cancel{\text{C}}} \times \frac{16.05\ \text{g CH}_4}{1\ \cancel{\text{mol}}\ \cancel{\text{CH}_4}} \\
m_{\text{CH}_4} &= 13.4\ \text{kg}
\end{aligned}
$$

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\%\ \text{yield} = \frac{4.20\ \cancel{\text{kg}}}{13.4\ \cancel{\text{kg}}} \times 100\% = 31.4\%$$

The percentage yield of methane in this reaction is 31.4%.

(b) If the coal is only 40% carbon, then the percentage yield of methane is increased by a factor of 100/40. The percentage yield of methane in this reaction becomes 31.4% × 100/40 = 78.6%.

Making Connections

12. (a) Water is a preferable (nonpolluting) solvent.
(b) Room temperature reactions don’t require energy input.
(c) Drying agents are less acceptable — they add an extra chemical.
(d) Purification is less preferred — it will take energy and maybe more chemicals.
(e) Biomass is preferable because it is a renewable resource.

SECTION 5.6 QUESTIONS

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Understanding Concepts

1. (a) Yield in school experiments can be improved mostly by being careful (e.g., using only clean equipment), following procedure, and using good technique.
   (b) Yields in industrial processes can be improved by adjusting reaction conditions, and sometimes by following a different reaction sequence.
2. (a)

$$\begin{array}{lllllll} C_7H_6O_{3(s)} & + & C_4H_6O_{3(s)} & \rightarrow & C_9H_8O_{4(s)} & + & C_2H_4O_{2(s)} \\ 2.00\text{ g} & & 4.00\text{ g} & & & & \\ 138.13\text{ g/mol} & & 102.10\text{ g/mol} & & & & \end{array}$$

$$n_{C_7H_6O_3} = 2.00\ \cancel{g} \times \frac{1\text{ mol}}{138.13\ \cancel{g}}$$

$$n_{C_7H_6O_3} = 0.0145\text{ mol}$$

$$n_{C_4H_6O_3} = 4.00\ \cancel{g} \times \frac{1\text{ mol}}{102.10\ \cancel{g}}$$

$$n_{C_4H_6O_3} = 0.0392\text{ mol}$$

Since the reactant mole ratio is 1:1, the $C_7H_6O_{3(s)}$ is obviously the limiting reagent for this reaction.

$$\begin{array}{lllllll} C_7H_6O_{3(s)} & + & C_4H_6O_{3(s)} & \rightarrow & C_9H_8O_{4(s)} & + & C_2H_4O_{2(s)} \\ 2.00\text{ g} & & & & m\text{ (2.09 g actual)} & & \\ 138.13\text{ g/mol} & & & & 180.17\text{ g/mol} & & \end{array}$$

$$n_{C_7H_6O_3} = 2.00\ \cancel{g} \times \frac{1\text{ mol}}{138.13\ \cancel{g}}$$

$$n_{C_7H_6O_3} = 0.0145\text{ mol}$$

$$n_{C_9H_8O_4} = 0.0145\text{ mol} \times \frac{1}{1}$$

$$n_{C_9H_8O_4} = 0.0145\text{ mol}$$

$$m_{C_9H_8O_4} = 0.0145\ \cancel{\text{mol}} \times \frac{180.17\text{ g}}{1\ \cancel{\text{mol}}}$$

$$m_{C_9H_8O_4} = 2.61\text{ g}$$

or

$$m_{C_9H_8O_4} = 2.00\ \cancel{g}\ \cancel{C_7H_6O_3} \times \frac{1\ \cancel{\text{mol}}\ \cancel{C_7H_6O_3}}{138.13\ \cancel{g}\ \cancel{C_7H_6O_3}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{C_9H_8O_4}}{1\ \cancel{\text{mol}}\ \cancel{C_7H_6O_3}} \times \frac{180.17\text{ g }C_9H_8O_4}{1\ \cancel{\text{mol}}\ \cancel{C_9H_8O_4}}$$

$$n_{C_9H_8O_4} = 2.61\text{ g}$$

The theoretical yield of Aspirin would be 2.61 g.

(b) $$\%\text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\%\text{ yield} = \frac{2.09\ \cancel{g}}{2.61\ \cancel{g}} \times 100\% = 80.1\%$$

The percentage yield of Aspirin in this reaction is 80.1%.

Applying Inquiry Skills

3. (a) **Experimental Design**

A measured sample of sodium silicate is dissolved and reacted with an excess of iron(III) nitrate in solution. The resulting precipitate is filtered, washed, and dried to allow measurement of its mass.

Procedure

A typical student procedure will be very similar to the one created for Investigation 5.5.1. It should be preceded by a calculation to determine what mass of iron(III) nitrate (per gram of sodium silicate) is required to ensure an excess.

(b) **Evaluation**

A percentage yield of 80% is very low for a precipitation reaction. This would probably indicate that the precipitate remained at least partly dissolved in the original solution, or dissolved to some extent in the wash water. Obviously, a different process must be tried to improve the yield.

Making Connections

4. There are many "green" projects for students to research — one example might be the work on fuel cells to allow cars to run on hydrogen, thus reducing pollutant levels significantly.

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5. Student reports will be specific to the educational institution they choose and especially to the person they choose to interview. The report should concentrate on educational requirements, and the nature of the workday.

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5.7 CHEMISTRY IN TECHNOLOGY

PRACTICE

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Understanding Concepts

1. Inspection of the reaction equations shows that all mole ratios in each step are 1:1, so two moles (in total) of hydrochloric acid are produced for each one mole of sodium carbonate produced.
2. The LeBlanc process was expensive because it required using a large amount of fuel for heat.
3. Air pollutants were a matter of personal concern to people affected directly by them in these centuries, but no government had, as yet, considered that controlling pollutants was its responsibility. People in general were not aware of long-term health hazards or, indeed, of specific pollution hazards, other than odours and skin or lung irritation. Also, because industries were smaller and relatively few in number, pollutant effects tended to be local rather than widespread.

PRACTICE

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Understanding Concepts

4. (a) $CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$

   (b) $CO_{2(g)} + NH_{3(aq)} + H_2O_{(l)} \rightarrow NH_4HCO_{3(aq)}$

   (c) $NH_4HCO_{3(aq)} + NaCl_{(aq)} \rightarrow NH_4Cl_{(aq)} + NaHCO_{3(s)}$

   (d) $2\ NaHCO_{3(s)} \rightarrow Na_2CO_{3(s)} + H_2O_{(g)} + CO_{2(g)}$

   (e) $CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2(s)}$

   (f) $Ca(OH)_{2(s)} + 2\ NH_4Cl_{(aq)} \rightarrow 2\ NH_{3(g)} + CaCl_{2(aq)} + 2\ H_2O_{(l)}$

   (g) $CaCO_{3(s)} + 2\ NaCl_{(aq)} \rightarrow Na_2CO_{3(s)} + CaCl_{2(aq)}$ (from text, p. 247)

5. (i) $CaCO_{3(s)} \rightarrow \cancel{CaO}_{(s)} + \cancel{CO}_{2(g)}$

   (ii) $\cancel{CO}_{2(g)} + \cancel{NH}_{3(aq)} + \cancel{H_2O}_{(l)} \rightarrow NH\cancel{_4H}CO_{3\,(aq)}$

   (iii) $NH\cancel{_4H}CO_{3(aq)} + NaCl_{(aq)} \rightarrow N\cancel{H_4}Cl_{\,(aq)} + Na\cancel{H}CO_{3(s)}$

   (iv) $2\ Na\cancel{H}CO_{3(s)} \rightarrow Na_2CO_{3(s)} + \cancel{H_2O}_{(g)} + \cancel{CO}_{2(g)}$

   (v) $\cancel{CaO}_{(s)} + \cancel{H_2O}_{(l)} \rightarrow Ca\cancel{(O}H)_{2\,(s)}$

(vi) $Ca\cancel{(OH)}_{2\,(s)} + 2\,N\cancel{H_4}Cl_{(aq)} \rightarrow 2\,\cancel{NH}_{3(g)} + CaCl_{2(aq)} + 2\,\cancel{H_2O}_{(l)}$

Totalling the above, we get:
$CaCO_{3(s)} + 2\,NaCl_{(aq)} \rightarrow Na_2CO_{3(s)} + CaCl_{2(aq)}$

6. The raw materials are $CaCO_{3(s)}$ and $NaCl_{(s)}$, both of which are mined easily in large quantity.
7. The primary product is sodium carbonate (washing soda), $Na_2CO_{3(s)}$. The byproduct is calcium chloride, $CaCl_{2(s)}$.
8. Sodium hydrogen carbonate (sodium bicarbonate or baking soda), $NaHCO_{3(s)}$, is a marketable intermediate. Removing this intermediate from the reaction sequence means less sodium carbonate, $Na_2CO_{3(s)}$, will be produced, and some water and carbon dioxide must be added back into the reaction sequence.
9. Water and energy will also be required for this process.
10. Larger reaction scale is more efficient, and thus more economic. It does not cost twice as much to build a reaction vessel twice as large, nor are twice as many employees required to operate it, but it will produce twice as much product, and therefore, twice the value.

PRACTICE

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Making Connections

11. Industries may resist changing processes because of high restructuring costs (new manufacturing plants, new delivery methods, perhaps a need for new resources) and employee change/training/dislocation costs. The risk is loss of profitability; the benefit may not be sufficient, or may not be sufficiently well defined.
12. Consumers have input through consumer action groups, by personal complaints, and through government, but their primary input is the effect they have on the profitability of the process, through their decision to purchase or refuse to purchase the product.
13. Student discussion should include examples of percentage composition, stoichiometric reaction quantities, and percentage yield for the industrial chemical process chosen.

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SECTION 5.7 QUESTIONS

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Understanding Concepts

1. Science is the study of the natural world to describe, predict, and explain changes and substances; technology encompasses the skills, processes, and equipment required to make useful products or to perform useful tasks.
2. (a) Technological question.
   (b) Scientific question.
   (c) Scientific question.
   (d) Technological question.
   (e) Scientific question.
   (f) Technological question.
3. The LeBlanc process produced sodium carbonate (washing soda), which was in demand for glassmaking, among other things.
4. The LeBlanc process required a great quantity of costly fuel for energy, and produced a large quantity of undesirable pollutants.
5. Some (only a few) of the uses of Solvay products and a byproduct:
   (a) $Na_2CO_{3(s)}$ — cleaning compounds, pH control, food additive, glassmaking, chemical analysis.
   (b) $NaHCO_{3(s)}$ — baking powder, pharmaceuticals, sponge rubber, gold and platinum plating, fire extinguishers, cleaners, and antacids.
   (c) $CaCl_{2(s)}$ — de-icing, dust control on roads, fungicides, use in the paper industry, drying agent, and pharmaceuticals.

CHAPTER 5 REVIEW

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Understanding Concepts

1. (a) In a reagent mix, the one consumed first, causing the reaction to cease, is the limiting reagent. Some of the other reagent will remain, so it is said to be in excess.
   (b) A chemical reaction involves change in the electrons of an entity; a nuclear reaction involves change in the atomic nuclei.
   (c) Alpha decay involves the emission of an alpha particle (helium-4 nucleus) from an atomic nucleus, while beta decay involves the emission of a beta particle (electron) from a nucleus.
   (d) The quantity of product predicted by stoichiometric calculation is the theoretical yield. When the reaction is carried out, the measured quantity of product obtained is the actual yield.
   (e) An empirical formula shows the simplest integral ratio of component entities. A molecular formula shows the actual numerical ratio of atoms in a molecule of the substance.
2. (a) $2\ SO_{2(g)} + O_{2(g)} \rightarrow 2\ SO_{3(g)}$
   (b) $SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(aq)}$
   (c) $CaO_{(s)} + SO_{2(g)} \rightarrow O_{2(g)} + CaSO_{4(s)}$
   (d) $CaO_{(s)} + H_2SO_{3(aq)} \rightarrow H_2O_{(l)} + CaSO_{3(s)}$
   (e) $Al_2(SiO_3)_{3(s)} + 3\ H_2SO_{4(aq)} \rightarrow 3\ H_2SiO_{3(aq)} + Al_2(SO_4)_{3(s)}$
3. (a) ${}^{233}_{90}\text{Th} \rightarrow {}^{0}_{-1}\text{e} + {}^{233}_{91}\text{Pa}$
   (b) ${}^{233}_{91}\text{Pa} \rightarrow {}^{0}_{-1}\text{e} + {}^{233}_{92}\text{U}$
4. ${}^{131}_{53}\text{I} \rightarrow {}^{0}_{-1}\text{e} + {}^{131}_{54}\text{Xe}$
5. (a) ${}^{122}_{53}\text{I} \rightarrow {}^{122}_{54}\text{Xe} + {}^{0}_{-1}\text{e}$
   (b) ${}^{59}_{26}\text{Fe} \rightarrow {}^{59}_{27}\text{Co} + {}^{0}_{-1}\text{e}$
   (c) ${}^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\text{He}$
   (d) ${}^{252}_{98}\text{Cf} + {}^{10}_{5}\text{B} \rightarrow {}^{259}_{103}\text{Lr} + 3\ {}^{1}_{0}\text{n}$
   (e) ${}^{239}_{94}\text{Pu} + {}^{4}_{2}\text{He} \rightarrow {}^{242}_{96}\text{Cm} + {}^{1}_{0}\text{n}$
6. The mass number drops by 28, which means 28/4 = 7 alpha decays. The atomic number only drops by 10, which means 14 − 10 = 4 beta decays.
7. ${}^{190}_{75}\text{Re} \rightarrow {}^{190}_{76}\text{Os} + {}^{0}_{-1}\text{e}$

   ${}^{9}_{3}\text{Li} \rightarrow {}^{8}_{3}\text{Li} + {}^{1}_{0}\text{n}$

   ${}^{214}_{83}\text{Bi} \rightarrow {}^{210}_{79}\text{Au} + {}^{4}_{2}\text{He}$

   ${}^{162}_{69}\text{Tm} \rightarrow {}^{162}_{70}\text{Yb} + {}^{0}_{-1}\text{e}$

   ${}^{120}_{49}\text{In} \rightarrow {}^{120}_{50}\text{Sn} + {}^{0}_{-1}\text{e}$
8.

$2\ C_8H_{18(l)}$	+	$25\ O_{2(g)}$	$\rightarrow$	$16\ CO_{2(g)}$	+	$18\ H_2O_{(g)}$
692 g				m		
114.26 g/mol				44.01 g/mol		

$$n_{C_8H_{18}} = 692\ \cancel{g} \times \frac{1\ \text{mol}}{114.26\ \cancel{g}}$$

$$n_{C_8H_{18}} = 6.06\ \text{mol}$$

$$n_{CO_2} = 6.06\ \text{mol} \times \frac{16}{2}$$

$$\begin{aligned}
n_{CO_2} &= 48.5 \text{ mol}\\
m_{CO_2} &= 48.5 \cancel{\text{mol}} \times \frac{44.01 \text{ g}}{1 \cancel{\text{mol}}}\\
m_{CO_2} &= 2.13 \times 10^3 \text{ g} = 2.13 \text{ kg}
\end{aligned}$$

or

$$\begin{aligned}
m_{CO_2} &= 692 \cancel{\text{g}} \cancel{C_8H_{18}} \times \frac{1 \cancel{\text{mol}} \cancel{C_8H_{18}}}{114.26 \cancel{\text{g}} \cancel{C_8H_{18}}} \times \frac{16 \cancel{\text{mol}} \cancel{CO_2}}{2 \cancel{\text{mol}} \cancel{C_8H_{18}}} \times \frac{44.01 \text{ g } CO_2}{1 \cancel{\text{mol}} \cancel{CO_2}}\\
m_{CO_2} &= 2.13 \times 10^3 \text{ g} = 2.13 \text{ kg}
\end{aligned}$$

The mass of carbon dioxide formed is 2.13 kg.

9. (a)

$$\begin{array}{lllll}
WO_{3(s)} & + \; 3\,H_{2(g)} & \rightarrow & W_{(s)} & + \; 3\,H_2O_{(g)}\\
m & & & 5.00 \text{ g} & \\
231.85 \text{ g/mol} & & & 183.85 \text{ g/mol} &
\end{array}$$

$$\begin{aligned}
n_W &= 5.00 \cancel{\text{g}} \times \frac{1 \text{ mol}}{183.85 \cancel{\text{g}}}\\
n_W &= 0.0272 \text{ mol}\\
n_{WO_3} &= 0.0272 \text{ mol} \times \frac{1}{1}\\
n_{WO_3} &= 0.0272 \text{ mol}\\
m_{WO_3} &= 0.0272 \cancel{\text{mol}} \times \frac{231.85 \text{ g}}{1 \cancel{\text{mol}}}\\
m_{WO_3} &= 6.31 \text{ g}
\end{aligned}$$

or

$$\begin{aligned}
m_{WO_3} &= 5.00 \cancel{\text{g}} \cancel{W} \times \frac{1 \cancel{\text{mol}} \cancel{W}}{183.85 \cancel{\text{g}} \cancel{W}} \times \frac{1 \cancel{\text{mol}} \cancel{WO_3}}{1 \cancel{\text{mol}} \cancel{W}} \times \frac{231.85 \text{ g } WO_3}{1 \cancel{\text{mol}} \cancel{WO_3}}\\
m_{WO_3} &= 6.31 \text{ g}
\end{aligned}$$

The mass of tungsten(VI) oxide needed is 6.31 g.

(b)

$$\begin{array}{lllll}
WO_{3(s)} & + \; 3\,H_{2(g)} & \rightarrow & W_{(s)} \quad + & 3\,H_2O_{(g)}\\
 & & & 5.00 \text{ g} & m\\
 & & & 183.85 \text{ g/mol} & 18.02 \text{ g/mol}
\end{array}$$

$$\begin{aligned}
n_W &= 5.00 \cancel{\text{g}} \times \frac{1 \text{ mol}}{183.85 \cancel{\text{g}}}\\
n_W &= 0.0272 \text{ mol}\\
n_{H_2O} &= 0.0272 \text{ mol} \times \frac{3}{1}\\
n_{H_2O} &= 0.0816 \text{ mol}\\
m_{H_2O} &= 0.0816 \cancel{\text{mol}} \times \frac{18.02 \text{ g}}{1 \cancel{\text{mol}}}\\
m_{H_2O} &= 1.47 \text{ g}
\end{aligned}$$

or

$$\begin{aligned}
m_{H_2O} &= 5.00 \cancel{\text{g}} \cancel{W} \times \frac{1 \cancel{\text{mol}} \cancel{W}}{183.85 \cancel{\text{g}} \cancel{W}} \times \frac{3 \cancel{\text{mol}} \cancel{H_2O}}{1 \cancel{\text{mol}} \cancel{W}} \times \frac{18.02 \text{ g } H_2O}{1 \cancel{\text{mol}} \cancel{H_2O}}\\
m_{H_2O} &= 1.47 \text{ g}
\end{aligned}$$

The mass of water vapour produced is 1.47 g.

10. (a)

$$\begin{array}{lllllll}
HC_4H_7O_{2(l)} & + & C_2H_5OH_{(l)} & \rightarrow & C_4H_7O_2C_2H_{5(l)} & + & H_2O_{(l)}\\
30.0 \text{ g} & & 18.0 \text{ g} & & & & \\
88.12 \text{ g/mol} & & 46.08 \text{ g/mol} & & & &
\end{array}$$

$$\begin{aligned}
n_{HC_4H_7O_2} &= 30.0 \cancel{\text{g}} \times \frac{1 \text{ mol}}{88.12 \cancel{\text{g}}}\\
n_{HC_4H_7O_2} &= 0.340 \text{ mol}
\end{aligned}$$

$$n_{C_2H_5OH} = 18.0\ \cancel{g} \times \frac{1\ mol}{46.08\ \cancel{g}}$$

$$n_{C_2H_5OH} = 0.391\ mol$$

Since the reactant mole ratio is 1:1, the $HC_4H_7O_{2(l)}$ is obviously the limiting reagent for this reaction.

(b) $HC_4H_7O_{2(l)} \quad + \quad C_2H_5OH_{(l)} \quad \rightarrow \quad C_4H_7O_2C_2H_{5(l)} \quad + \quad H_2O_{(l)}$

30.0 g $\qquad\qquad\qquad\qquad$ m

88.12 g/mol $\qquad\qquad\qquad$ 116.18 g/mol

$$n_{HC_4H_7O_2} = 30.0\ \cancel{g} \times \frac{1\ mol}{88.12\ \cancel{g}}$$

$$n_{HC_4H_7O_2} = 0.340\ mol$$

$$n_{C_4H_7O_2C_2H_5} = 0.340\ mol \times \frac{1}{1}$$

$$n_{C_4H_7O_2C_2H_5} = 0.340\ mol$$

$$m_{C_4H_7O_2C_2H_5} = 0.340\ \cancel{mol} \times \frac{116.18\ g}{1\ \cancel{mol}}$$

$$m_{C_4H_7O_2C_2H_5} = 39.6\ g$$

or

$$m_{C_4H_7O_2C_2H_5} = 30.0\ \cancel{g}\ \cancel{HC_4H_7O_2} \times \frac{1\ \cancel{mol}\ \cancel{HC_4H_7O_2}}{\cancel{\qquad}} \times \frac{1\ \cancel{mol}\ \cancel{C_4H_7O_2C_2H_5}}{\cancel{\qquad}} \times \frac{116.18\ g\ C_4H_7O_2C_2H_5}{\cancel{\qquad}}$$

$$m_{C_4H_7O_2C_2H_5} = 39.6\ g$$

The mass of ethylbutanoate produced is 39.6 g.

11. Use the equation mole ratios in sequence: 1 mol $NH_{3(g)}$ reacts to form 1 mol $NO_{(g)}$; and 1 mol $NO_{(g)}$ reacts to form 1 mol $NO_{2(g)}$; and 1 mol $NO_{2(g)}$ reacts to form 2/3 mol $HNO_{3(aq)}$. This simplifies to: 1 mol $NH_{3(g)}$ reacts to form 2/3 mol $HNO_{3(aq)}$, or integrally, 3 mol $NH_{3(g)}$ react to form 2 mol $HNO_{3(aq)}$.

since $\qquad$ 3 $NH_{3(g)}$ react to form $\quad$ 2 $HNO_{3(aq)}$

4.00 mol $\qquad\qquad\qquad$ m

63.02 g/mol

$$n_{HNO_3} = 4.00\ mol \times \frac{2}{3}$$

$$n_{HNO_3} = 2.67\ mol$$

$$m_{HNO_3} = 2.67\ \cancel{mol} \times \frac{63.02\ g}{1\ \cancel{mol}}$$

$$m_{HNO_3} = 168\ g$$

or

$$m_{HNO_3} = 4.00\ \cancel{mol}\ \cancel{NH_3} \times \frac{2\ \cancel{mol}\ \cancel{HNO_3}}{3\ \cancel{mol}\ \cancel{NH_3}} \times \frac{63.02\ g\ HNO_3}{1\ \cancel{mol}\ \cancel{HNO_3}}$$

$$m_{HNO_3} = 168\ g$$

The mass of nitric acid produced is 168 g.

12. (a) $C_3H_5(OH)_{3(l)} + 3\ HNO_{3(aq)} \rightarrow \quad C_3H_5(NO_3)_{3(s)} + H_2O_{(l)}$

(b) $C_3H_5(OH)_{3(l)} + \ 3\ HNO_{3(aq)} \rightarrow \quad C_3H_5(NO_3)_{3(s)} + H_2O_{(l)}$

10.4 g $\qquad\qquad$ 19.2 g

92.11 g/mol $\qquad$ 63.02 g/mol

$$n_{C_3H_5(OH)_3} = 10.4\ \cancel{g} \times \frac{1\ mol}{92.11\ \cancel{g}}$$

$$n_{C_3H_5(OH)_3} = 0.113\ mol$$

$$n_{HNO_3} = 19.2\ \cancel{g} \times \frac{1\ mol}{63.02\ \cancel{g}}$$

$$n_{HNO_3} = 0.305\ mol$$

Since the reactant mole ratio is 1:3, 0.305 mol of $HNO_{3(aq)}$ would require 0.305 mol × 1/3 = 0.102 mol of $C_3H_5(OH)_{3(l)}$ to react completely. The amount of $C_3H_5(OH)_{3(l)}$ is in excess, so the $HNO_{3(aq)}$ is the limiting reagent for this reaction.

(c)
$$\begin{array}{lllll} C_3H_5(OH)_{3(l)} + & 3\ HNO_{3(aq)} & \rightarrow & C_3H_5(NO_3)_{3(s)} + & H_2O_{(l)} \\ & 19.2\text{ g} & & m\text{ (22.6 g actual)} & \\ & 63.02\text{ g/mol} & & 227.11\text{ g/mol} & \end{array}$$

$$\begin{aligned} n_{HNO_3} &= 19.2\ \cancel{\text{g}} \times \frac{1\text{ mol}}{63.02\ \cancel{\text{g}}} \\ n_{HNO_3} &= 0.305\text{ mol} \\ n_{C_3H_5(NO_3)_3} &= 0.305\text{ mol} \times \frac{1}{3} \\ n_{C_3H_5(NO_3)_3} &= 0.102\text{ mol} \\ m_{C_3H_5(NO_3)_3} &= 0.102\ \cancel{\text{mol}} \times \frac{227.11\text{ g}}{1\ \cancel{\text{mol}}} \\ m_{C_3H_5(NO_3)_3} &= 23.1\text{ g} \end{aligned}$$

or

$$\begin{aligned} m_{C_3H_5(NO_3)_3} &= 19.2\ \cancel{\text{g}\ HNO_3} \times \frac{1\ \cancel{\text{mol}\ HNO_3}}{63.02\ \cancel{\text{g}\ HNO_3}} \times \frac{1\ \cancel{\text{mol}\ C_3H_5(NO_3)_3}}{3\ \cancel{\text{mol}\ HNO_3}} \times \frac{227.11\text{ g } C_3H_5(NO_3)_3}{\cancel{\qquad\qquad}} \\ m_{C_3H_5(NO_3)_3} &= 23.1\text{ g} \end{aligned}$$

The theoretical yield of nitroglycerin should be 23.1 g.

(d) $\%\text{ yield} = \dfrac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

$$\%\text{ yield} = \frac{22.6\ \cancel{\text{g}}}{23.1\ \cancel{\text{g}}} \times 100\% = 97.8\%$$

The percentage yield of nitroglycerin in this reaction is 97.8%

13. Yield less than predicted in a reaction may be due to experimental error inherent in the procedure; to impurities in the reagents; to unwanted side reactions; and to reactions that are not quantitative — that do not "go to completion."

14. (a)
$$\begin{array}{lllllll} SiO_{2(s)} & + & 4\ HF_{(aq)} & \rightarrow & SiF_{4(g)} & + & 2\ H_2O_{(l)} \\ 6.80\text{ g} & & & & m & & \\ 60.09\text{ g/mol} & & & & 104.09\text{ g/mol} & & \end{array}$$

$$\begin{aligned} n_{SiO_2} &= 6.80\ \cancel{\text{g}} \times \frac{1\text{ mol}}{60.09\ \cancel{\text{g}}} \\ n_{SiO_2} &= 0.113\text{ mol} \\ n_{SiF_4} &= 0.113\text{ mol } \times \frac{1}{1} \\ n_{SiF_4} &= 0.113\text{ mol} \\ m_{SiF_4} &= 0.113\ \cancel{\text{mol}} \times \frac{104.09\text{ g}}{1\ \cancel{\text{mol}}} \\ m_{SiF_4} &= 11.8\ \text{ g} \end{aligned}$$

or

$$\begin{aligned} m_{SiF_4} &= 6.80\ \cancel{\text{g}\ SiO_2} \times \frac{1\ \cancel{\text{mol}\ SiO_2}}{60.09\ \cancel{\text{g}\ SiO_2}} \times \frac{1\ \cancel{\text{mol}\ SiF_4}}{1\ \cancel{\text{mol}\ SiO_2}} \times \frac{104.09\text{ g } SiF_4}{1\ \cancel{\text{mol}\ SiF_4}} \\ m_{SiF_4} &= 11.8\ \text{ g} \end{aligned}$$

The mass of silicon tetrafluoride produced is 11.8 g.

(b)
$$\begin{array}{lllllll} SiO_{2(s)} & + & 4\ HF_{(aq)} & \rightarrow & SiF_{4(g)} & + & 2\ H_2O_{(l)} \\ 53.2\text{ g} & & m & & & & \\ 60.09\text{ g/mol} & & 20.01\text{ g/mol} & & & & \end{array}$$

$$\begin{aligned} n_{SiO_2} &= 53.2\ \cancel{\text{g}} \times \frac{1\text{ mol}}{60.09\ \cancel{\text{g}}} \\ n_{SiO_2} &= 0.885\text{ mol} \end{aligned}$$

$$\begin{aligned}
n_{HF} &= 0.885\ \text{mol}\ \times \frac{4}{1} \\
n_{HF} &= 3.54\ \text{mol} \\
m_{HF} &= 3.54\ \cancel{\text{mol}} \times \frac{20.01\ \text{g}}{1\ \cancel{\text{mol}}} \\
m_{HF} &= 70.9\ \ \text{g}
\end{aligned}$$

or

$$\begin{aligned}
m_{HF} &= 53.2\ \cancel{\text{g}}\ \cancel{SiO_2} \times \frac{1\ \cancel{\text{mol}}\ \cancel{SiO_2}}{60.09\ \cancel{\text{g}}\ \cancel{SiO_2}} \times \frac{4\ \cancel{\text{mol}}\ \cancel{HF}}{1\ \cancel{\text{mol}}\ \cancel{SiO_2}} \times \frac{20.01\ \text{g HF}}{1\ \cancel{\text{mol}}\ \cancel{HF}} \\
m_{HF} &= 70.9\ \ \text{g}
\end{aligned}$$

The mass of hydrofluoric acid required is 70.9 g.

(c)
$$\begin{array}{lllllll}
SiO_{2(s)} & + & 4\ HF_{(aq)} & \rightarrow & SiF_{4(g)} & + & 2\ H_2O_{(l)} \\
10.6\ \text{g} & & & & & & m \\
60.09\ \text{g/mol} & & & & & & 18.02\ \text{g/mol}
\end{array}$$

$$\begin{aligned}
n_{SiO_2} &= 10.6\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{60.09\ \cancel{\text{g}}} \\
n_{SiO_2} &= 0.176\ \text{mol} \\
n_{H_2O} &= 0.176\ \text{mol}\ \times \frac{2}{1} \\
n_{H_2O} &= 0.353\ \text{mol} \\
m_{H_2O} &= 0.353\ \cancel{\text{mol}} \times \frac{18.02\ \text{g}}{1\ \cancel{\text{mol}}} \\
m_{H_2O} &= 6.36\ \ \text{g}
\end{aligned}$$

or

$$\begin{aligned}
m_{H_2O} &= 10.6\ \cancel{\text{g}}\ \cancel{SiO_2} \times \frac{1\ \cancel{\text{mol}}\ \cancel{SiO_2}}{60.09\ \cancel{\text{g}}\ \cancel{SiO_2}} \times \frac{2\ \cancel{\text{mol}}\ \cancel{H_2O}}{1\ \cancel{\text{mol}}\ \cancel{SiO_2}} \times \frac{18.02\ \text{g}\ H_2O}{1\ \cancel{\text{mol}}\ \cancel{H_2O}} \\
m_{H_2O} &= 6.36\ \ \text{g}
\end{aligned}$$

The mass of water produced is 6.36 g.

15. (a) $C_2H_5OH_{(l)} + \quad 3\ O_{2(g)} \quad \rightarrow \quad 2\ CO_{2(g)} \quad + \quad 3\ H_2O_{(g)}$

(b)
$$\begin{array}{lllllll}
C_2H_5OH_{(l)} & + & 3\ O_{2(g)} & \rightarrow & 2\ CO_{2(g)} & + & 3\ H_2O_{(g)} \\
450.0\ \text{g} & & & & m & & \\
46.08\ \text{g/mol} & & & & 44.01\ \text{g/mol} & &
\end{array}$$

$$\begin{aligned}
n_{C_2H_5OH} &= 450.0\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{46.08\ \cancel{\text{g}}} \\
n_{C_2H_5OH} &= 9.766\ \text{mol} \\
n_{CO_2} &= 9.766\ \text{mol}\ \times \frac{2}{1} \\
n_{CO_2} &= 19.53\ \text{mol} \\
m_{CO_2} &= 19.53\ \cancel{\text{mol}} \times \frac{44.01\ \text{g}}{1\ \cancel{\text{mol}}} \\
m_{CO_2} &= 859.6\ \ \text{g}
\end{aligned}$$

or

$$\begin{aligned}
m_{CO_2} &= 450.0\ \cancel{\text{g}}\ C_2\cancel{H_5}OH \times \frac{1\ \cancel{\text{mol}}\ C_2\cancel{H_5}OH}{\ } \times \frac{2\ \cancel{\text{mol}}\ \cancel{CO_2}}{1\ \cancel{\text{mol}}\ C_2\cancel{H_5}OH} \times \frac{44.01\ \text{g}\ CO_2}{1\ \cancel{\text{mol}}\ \cancel{CO_2}} \\
m_{CO_2} &= 859.6\ \ \text{g}
\end{aligned}$$

The mass of carbon dioxide produced is 859.6 g.

(c)
$$\begin{array}{lllllll}
C_2H_5OH_{(l)} & + & 3\ O_{2(g)} & \rightarrow & 2\ CO_{2(g)} & + & 3\ H_2O_{(g)} \\
450.0\ \text{g} & & & & & & m
\end{array}$$

46.08 g/mol 18.02 g/mol

$$n_{C_2H_5OH} = 450.0\ \cancel{g} \times \frac{1\ mol}{46.08\ \cancel{g}}$$
$$n_{C_2H_5OH} = 9.766\ mol$$
$$n_{H_2O} = 9.766\ mol \times \frac{3}{1}$$
$$n_{H_2O} = 29.30\ mol$$
$$m_{H_2O} = 29.30\ \cancel{mol} \times \frac{18.02\ g}{1\ \cancel{mol}}$$
$$m_{H_2O} = 527.9\ g$$

or

$$m_{H_2O} = 450.0\ \cancel{g}\ C_2\cancel{H_5OH} \times \frac{1\ \cancel{mol}\ C_2\cancel{H_5OH}}{46.08\ \cancel{g}\ C_2\cancel{H_5OH}} \times \frac{3\ \cancel{mol}\ \cancel{H_2O}}{1\ \cancel{mol}\ C_2\cancel{H_5OH}} \times \frac{18.02\ g\ H_2O}{1\ \cancel{mol}\ \cancel{H_2O}}$$
$$m_{H_2O} = 527.9\ g$$

The mass of water produced is 527.9 g.

(d) $C_2H_5OH_{(l)} + 3\ O_{2(g)} \rightarrow 2\ CO_{2(g)} + 3\ H_2O_{(g)}$

450.0 g	m		
46.08 g/mol	32.00 g/mol		

$$n_{C_2H_5OH} = 450.0\ \cancel{g} \times \frac{1\ mol}{46.08\ \cancel{g}}$$
$$n_{C_2H_5OH} = 9.766\ mol$$
$$n_{O_2} = 9.766\ mol \times \frac{3}{1}$$
$$n_{O_2} = 29.30\ mol$$
$$m_{O_2} = 29.30\ \cancel{mol} \times \frac{32.00\ g}{1\ \cancel{mol}}$$
$$m_{O_2} = 937.5\ g$$

or

$$m_{O_2} = 450.0\ \cancel{g}\ C_2\cancel{H_5OH} \times \frac{1\ \cancel{mol}\ C_2\cancel{H_5OH}}{46.08\ \cancel{g}\ C_2\cancel{H_5OH}} \times \frac{3\ \cancel{mol}\ \cancel{O_2}}{1\ \cancel{mol}\ C_2\cancel{H_5OH}} \times \frac{32.00\ g\ O_2}{1\ \cancel{mol}\ \cancel{O_2}}$$
$$m_{O_2} = 937.5\ g$$

The mass of oxygen required is 937.5 g.

(e) $C_2H_5OH_{(l)} + 3\ O_{2(g)} \rightarrow 2\ CO_{2(g)} + 3\ H_2O_{(g)}$

The masses involved, respectively, in this reaction are:

450.0 g	937.5 g	859.6 g	527.9 g

Addition shows that (450.0 + 937.5) = (859.6 + 527.9) = 1387.5, so the result agrees with the law of conservation of mass.

16. $2\ CuO_{(s)} + C_{(s)} \rightarrow 2\ Cu_{(s)} + CO_{2(g)}$

50.0 kg	m		
79.55 g/mol 1	2.01 g/mol		

$$n_{CuO} = 50.0\ k\cancel{g} \times \frac{1\ mol}{79.55\ \cancel{g}}$$
$$n_{CuO} = 0.629\ kmol$$
$$n_C = 0.629\ kmol \times \frac{1}{2}$$
$$n_C = 0.314\ kmol$$
$$m_C = 0.314\ k\cancel{mol} \times \frac{12.01\ g}{1\ \cancel{mol}}$$

m_C = 3.77 kg

or

$$m_C = 50.0 \text{ k}\cancel{\text{g}}\ \cancel{\text{CuO}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{CuO}}}{79.55\ \cancel{\text{g}}\ \cancel{\text{CuO}}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{\text{C}}}{2\ \cancel{\text{mol}}\ \cancel{\text{CuO}}} \times \frac{12.01\ \text{g C}}{1\ \cancel{\text{mol}}\ \cancel{\text{C}}}$$

m_C = 3.77 kg

The mass of carbon required is 3.77 kg.

Applying Inquiry Skills

17. A solid reaction product can be removed (by filtration, for instance) from the reaction system. If some more of the (presumed) excess reagent is added, and no reaction occurs, then the limiting reagent is completely reacted and the other reagent is present in excess.

18. (a) **Prediction**

$$\begin{array}{lllllllll} Na_2SO_{4(aq)} & + & BaCl_{2(aq)} & \rightarrow & 2\ NaCl_{(aq)} & + & BaSO_{4(s)} \\ 142.04\text{ g/mol} & & & & & & 233.39\text{ g/mol} \end{array}$$

Since the substances are in a 1 : 1 mole ratio, the mass ratio of $BaSO_{4(s)}$: $Na_2SO_{4(aq)}$ will be 233.39 : 142.04 or 1.6431 : 1.0000. This means that for each 1.0000 g of sodium sulfate reacted, 1.6431 g of barium sulfate should be produced.

(b) **Experimental Design**

A measured mass of sodium sulfate is dissolved and reacted with excess barium chloride solution. The precipitate is filtered, dried, and weighed.

(c) **Procedure**

1. Use a clean, dry 250-mL beaker to obtain a 2.00 g sample of $Na_2SO_{4(aq)}$.
2. Use a 100-mL graduated cylinder to add approximately 50 mL of $BaCl_{2(aq)}$ to the beaker.
3. Allow the precipitate to settle, and test the clear liquid above the precipitate (the supernatant liquid) with a small amount of the $BaCl_{2(aq)}$ from a medicine dropper to see if further precipitation occurs.
4. If the test in step 3 indicates the reaction is not yet complete, repeat step 3 until no further precipitation occurs.
5. Measure and record the mass of a piece of filter paper to 0.01 g.
6. Filter, wash, and dry the $BaSO_{4(s)}$ precipitate.
7. Measure and record the mass of the filter paper plus dry precipitate to 0.01 g.
8. Dispose of all waste materials according to instructions.

(d) **Analysis**

To determine the purity of the sample, the percentage yield of the $BaSO_{4(s)}$ precipitate is calculated.

$$\%\text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

The $BaSO_{4(s)}$ percentage yield represents the purity of the sodium sulfate reagent as a percentage.

(e) **Evaluation**

This analysis assumes: that the other reagent is pure; that the precipitate is negligibly soluble; and that the experimental error is negligible. If any of these assumptions are incorrect, the actual yield value will be affected.

Making Connections

19. The report for this question should emphasize primarily the social perspective (the advantage of increased food supply) and the environmental perspective (the disadvantage of water pollution) as a typical tradeoff involving technology.