Stoichiometry

So far in your chemistry course, you have learned that chemists count quantities of elements and compounds in terms of moles and that they relate moles of a substance to mass by using the molar mass. In addition, you have learned to write chemical equations so that they represent the rearrangements of atoms that take place during chemical reactions, and you have learned to balance these equations. In this chapter you will be able to put these separate skills together to accomplish one of the most important tasks of chemistry—using chemical equations to make predictions about the quantities of substances that react or are given off as products and relating those quantities to one another. This process of relating quantities of reactants and products in a chemical reaction to one another is called stoichiometry.

First, look at an analogy.

Suppose you need to make several sandwiches to take on a picnic with friends. You decide to make turkey-and-cheese sandwiches using the following “equation:"

\[
\text{2 bread slices} + \text{2 turkey slices} + \text{1 lettuce leaf} + \text{1 cheese slice} \rightarrow \text{1 turkey-and-cheese sandwich}
\]

This equation shows that you need those ingredients in a ratio of 2:2:1:1, respectively. You can use this equation to predict that you would need 30 turkey slices to make 15 sandwiches or 6 cheese slices to go with 12 turkey slices.

Zinc reacts with oxygen according to the following balanced chemical equation:

\[
2\text{Zn} + \text{O}_2 \rightarrow 2\text{ZnO}
\]

Like the sandwich recipe, this equation can be viewed as a “recipe” for zinc oxide. It tells you that reacting two zinc atoms with a molecule of oxygen will produce two formula units of zinc oxide. Can you predict how many zinc oxide units could be formed from 500 zinc atoms? Could you determine how many moles of oxygen molecules it would take to react with 4 mol of zinc atoms? What if you had 22 g of zinc and wanted to know how many grams of ZnO could be made from it? Keep in mind that the chemical equation relates amounts, not masses, of products and reactants. The problems in this chapter will show you how to solve problems of this kind.
**General Plan for Solving Stoichiometry Problems**

1. **Mass of substance A**
   - Convert using the molar mass of A.

2. **Amount in mol of substance A**
   - Convert using the mole ratio \( \frac{A}{B} \) given in the balanced chemical equation.

3. **Amount in mol of substance B**
   - Convert using the molar mass of B.

4. **Mass of substance B**
Sample Problem 1
Ammonia is made industrially by reacting nitrogen and hydrogen under pressure, at high temperature, and in the presence of a catalyst. The equation is $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$. If 4.0 mol of $H_2$ react, how many moles of $NH_3$ will be produced?

Solution
ANALYZE
What is given in the problem? the balanced equation, and the amount of $H_2$ in moles
What are you asked to find? the amount of $NH_3$ produced in moles
Organization of data is extremely important in dealing with stoichiometry problems. You will find that it is most helpful to make data tables such as the following one.

<table>
<thead>
<tr>
<th>Items</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substance</td>
<td>$H_2$</td>
</tr>
<tr>
<td></td>
<td>$NH_3$</td>
</tr>
<tr>
<td>Coefficient in balanced equation</td>
<td>3</td>
</tr>
<tr>
<td>Molar mass</td>
<td>NA*</td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Amount</td>
<td>4.0 mol</td>
</tr>
<tr>
<td></td>
<td>? mol</td>
</tr>
<tr>
<td>Mass of substance</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
</tbody>
</table>

* NA means not applicable to the problem

PLAN
What steps are needed to calculate the amount of $NH_3$ that can be produced from 4.0 mol $H_2$?
Multiply by the mole ratio of $NH_3$ to $H_2$ determined from the coefficients of the balanced equation.

$$\frac{2}{3} \text{ mol } H_2 \times \frac{2 \text{ mol } NH_3}{3 \text{ mol } H_2} = \text{ mol } NH_3$$
**Problem Solving continued**

**COMPUTE**

\[ 4.0 \text{ mol H}_2 \times \frac{2 \text{ mol NH}_3}{3 \text{ mol H}_2} = 2.7 \text{ mol NH}_3 \]

**EVALUATE**

Are the units correct?
Yes; the answer has the correct units of moles NH\(_3\).

Is the number of significant figures correct?
Yes; two significant figures is correct because data were given to two significant figures.

Is the answer reasonable?
Yes; the answer is 2/3 of 4.0.

**Practice**

1. How many moles of sodium will react with water to produce 4.0 mol of hydrogen in the following reaction?

\[ 2\text{Na(s)} + 2\text{H}_2\text{O(l)} \rightarrow 2\text{NaOH(aq)} + \text{H}_2(g) \text{ ans: } 8.0 \text{ mol Na} \]

2. How many moles of lithium chloride will be formed by the reaction of chlorine with 0.046 mol of lithium bromide in the following reaction?

\[ 2\text{LiBr(aq)} + \text{Cl}_2(g) \rightarrow 2\text{LiCl(aq)} + \text{Br}_2(l) \text{ ans: } 0.046 \text{ mol LiCl} \]
3. Aluminum will react with sulfuric acid in the following reaction.

\[ 2\text{Al}(s) + 3\text{H}_2\text{SO}_4(l) \rightarrow \text{Al}_2(\text{SO}_4)_3(aq) + 3\text{H}_2(g) \]

a. How many moles of \( \text{H}_2\text{SO}_4 \) will react with 18 mol \( \text{Al} \)? \textbf{ans: 27 mol \( \text{H}_2\text{SO}_4 \)}

b. How many moles of each product will be produced? \textbf{ans: 27 mol \( \text{H}_2 \), 9 mol \( \text{Al}_2(\text{SO}_4)_3 \)}

4. Propane burns in excess oxygen according to the following reaction.

\[ \text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} \]

a. How many moles each of \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) are formed from 3.85 mol of propane? \textbf{ans: 11.6 mol \( \text{CO}_2 \), 15.4 mol \( \text{H}_2\text{O} \)}

b. If 0.647 mol of oxygen is used in the burning of propane, how many moles each of \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) are produced? How many moles of \( \text{C}_3\text{H}_8 \) are consumed? \textbf{ans: 0.388 mol \( \text{CO}_2 \), 0.518 mol \( \text{H}_2\text{O} \), 0.129 mol \( \text{C}_3\text{H}_8 \)}
Sample Problem 2

Potassium chlorate is sometimes decomposed in the laboratory to generate oxygen. The reaction is \(2\text{KClO}_3(s) \rightarrow 2\text{KCl}(s) + 3\text{O}_2(g)\). What mass of \(\text{KClO}_3\) do you need to produce 0.50 mol \(\text{O}_2\)?

Solution

**ANALYZE**

What is given in the problem?  the amount of oxygen in moles

What are you asked to find?  the mass of potassium chlorate

<table>
<thead>
<tr>
<th>Items</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substance</td>
<td>(\text{KClO}_3)</td>
</tr>
<tr>
<td>Coefficient in balanced equation</td>
<td>2</td>
</tr>
<tr>
<td>Molar mass*</td>
<td>122.55 g/mol</td>
</tr>
<tr>
<td>Amount</td>
<td>? mol</td>
</tr>
<tr>
<td>Mass</td>
<td>? g</td>
</tr>
</tbody>
</table>

* determined from the periodic table

**PLAN**

What steps are needed to calculate the mass of \(\text{KClO}_3\) needed to produce 0.50 mol \(\text{O}_2\)?

Use the mole ratio to convert amount of \(\text{O}_2\) to amount of \(\text{KClO}_3\). Then convert amount of \(\text{KClO}_3\) to mass of \(\text{KClO}_3\).

\[
\begin{align*}
\text{Amount of } \text{O}_2 \text{ in mol} & \quad \text{multiply by mole ratio} \quad \text{Amount of } \text{KClO}_3 \text{ in mol} \quad \text{multiply by molar mass of } \text{KClO}_3 \quad \text{Mass of } \text{KClO}_3 \text{ in g} \\
\text{given } \text{mol } \text{O}_2 & \times \frac{2 \text{ mol } \text{KClO}_3}{3 \text{ mol } \text{O}_2} & \text{mole ratio} & \times \frac{122.55 \text{ g } \text{KClO}_3}{1 \text{ mol } \text{KClO}_3} \quad & \text{g } \text{KClO}_3 \\
0.50 \text{ mol } \text{O}_2 & \times \frac{2 \text{ mol } \text{KClO}_3}{3 \text{ mol } \text{O}_2} & \frac{122.55 \text{ g } \text{KClO}_3}{1 \text{ mol } \text{KClO}_3} & = 41 \text{ g } \text{KClO}_3
\end{align*}
\]

**COMPUTE**

\[
0.50 \text{ mol } \text{O}_2 \times \frac{2 \text{ mol } \text{KClO}_3}{3 \text{ mol } \text{O}_2} \times \frac{122.55 \text{ g } \text{KClO}_3}{1 \text{ mol } \text{KClO}_3} = 41 \text{ g } \text{KClO}_3
\]

**EVALUATE**

Are the units correct?
Yes; units canceled to give grams of \(\text{KClO}_3\).
Problem Solving continued

Is the number of significant figures correct?
Yes; two significant figures is correct.

Is the answer reasonable?
Yes; 41 g is about 1/3 of the molar mass of KClO₃, and 0.5 × 2/3 = 1/3.

Practice

1. Phosphorus burns in air to produce a phosphorus oxide in the following reaction:

   4P(s) + 5O₂(g) → P₄O₁₀(s)

   a. What mass of phosphorus will be needed to produce 3.25 mol of P₄O₁₀?
      ans: 403 g P

   b. If 0.489 mol of phosphorus burns, what mass of oxygen is used? What mass of P₄O₁₀ is produced? ans: 19.6 g O₂, 15.4 g P₂O₄

2. Hydrogen peroxide breaks down, releasing oxygen, in the following reaction:

   2H₂O₂(aq) → 2H₂O(l) + O₂(g)

   a. What mass of oxygen is produced when 1.840 mol of H₂O₂ decomposes?
      ans: 29.44 g O₂

   b. What mass of water is produced when 5.0 mol O₂ is produced by this reaction? ans: 180 g H₂O
Sample Problem 3
How many moles of aluminum will be produced from 30.0 kg Al₂O₃ in the following reaction?

\[ 2\text{Al}_2\text{O}_3 \rightarrow 4\text{Al} + 3\text{O}_2 \]

Solution

ANALYZE
What is given in the problem?  the mass of aluminum oxide
What are you asked to find?  the amount of aluminum produced

<table>
<thead>
<tr>
<th>Items</th>
<th>Data</th>
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<tr>
<td>Substance</td>
<td>Al₂O₃</td>
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<td>Coefficient in balanced equation</td>
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<tr>
<td>Molar mass</td>
<td>101.96 g/mol</td>
</tr>
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<td>Amount</td>
<td>? mol</td>
</tr>
<tr>
<td>Mass</td>
<td>30.0 kg</td>
</tr>
</tbody>
</table>

PLAN
What steps are needed to calculate the amount of Al produced from 30.0 kg of Al₂O₃?
The molar mass of Al₂O₃ can be used to convert to moles Al₂O₃. The mole ratio of Al:Al₂O₃ from the coefficients in the equation will convert to moles Al from moles Al₂O₃.

1. Mass of Al₂O₃ in g → Mass of Al₂O₃ in kg
   - Multiply by the inverse of the molar mass of Al₂O₃
   - Multiply by \( \frac{1000 \text{ g}}{1 \text{ kg}} \)

2. Amount of Al₂O₃ in mol
   - Multiply by the mole ratio \( \frac{4 \text{ mol Al}}{2 \text{ mol Al₂O₃}} \)

3. Amount of Al in mol
   - Multiply by \( \frac{1 \text{ mol Al₂O₃}}{101.96 \text{ g Al₂O₃}} \)
   - Multiply by \( \frac{4 \text{ mol Al}}{2 \text{ mol Al₂O₃}} \)

COMPUTE

\[ 30.0 \text{ kg Al₂O₃} \times \frac{1000 \text{ g}}{\text{kg}} \times \frac{1 \text{ mol Al₂O₃}}{101.96 \text{ g Al₂O₃}} \times \frac{4 \text{ mol Al}}{2 \text{ mol Al₂O₃}} = 588 \text{ mol Al} \]
Problem Solving continued

EVALUATE
Are the units correct?
Yes; units canceled to give moles of Al.

Is the number of significant figures correct?
Yes; three significant figures is correct.

Is the answer reasonable?
Yes; the molar mass of Al₂O₃ is about 100, so 30 kg of Al₂O₃ is about 300 mol.
The mole ratio of Al:Al₂O₃ is 2:1, so the answer should be about 600 mol Al.

Practice

1. Sodium carbonate reacts with nitric acid according to the following equation.
   \[
   \text{Na}_2\text{CO}_3(s) + 2\text{HNO}_3 \rightarrow 2\text{NaNO}_3 + \text{CO}_2 + \text{H}_2\text{O}
   \]
   a. How many moles of Na₂CO₃ are required to produce 100.0 g of NaNO₃?
      \[\text{ans: 0.5882 mol Na}_2\text{CO}_3\]
   b. If 7.50 g of Na₂CO₃ reacts, how many moles of CO₂ are produced?
      \[\text{ans: 0.0708 mol CO}_2\]

2. Hydrogen is generated by passing hot steam over iron, which oxidizes to form Fe₃O₄, in the following equation.
   \[
   3\text{Fe}(s) + 4\text{H}_2\text{O}(g) \rightarrow 4\text{H}_2(g) + \text{Fe}_3\text{O}_4(s)
   \]
   a. If 625 g of Fe₃O₄ is produced in the reaction, how many moles of hydrogen are produced at the same time?
      \[\text{ans: 10.8 mol H}_2\]
   b. How many moles of iron would be needed to generate 27 g of hydrogen?
      \[\text{ans: 10. mol Fe}\]
Sample Problem 4

Methane burns in air by the following reaction:

\[ \text{CH}_4(g) + 2\text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(g) \]

What mass of water is produced by burning 500. g of methane?

Solution

ANALYZE

What is given in the problem?  the mass of methane in grams
What are you asked to find?  the mass of water produced

PLAN

What steps are needed to calculate the mass of \( \text{H}_2\text{O} \) produced from the burning of 500. g of \( \text{CH}_4 \)?

Convert grams of \( \text{CH}_4 \) to moles \( \text{CH}_4 \) by using the molar mass of \( \text{CH}_4 \). Use the mole ratio from the balanced equation to determine moles \( \text{H}_2\text{O} \) from moles \( \text{CH}_4 \).

Use the molar mass of \( \text{H}_2\text{O} \) to calculate grams \( \text{H}_2\text{O} \).

1. Mass of \( \text{CH}_4 \) in g
   multiply by the inverse of the molar mass of \( \text{CH}_4 \)

2. Amount of \( \text{CH}_4 \) in mol
   multiply by the mole ratio
   \[ \frac{2 \text{ mol H}_2\text{O}}{1 \text{ mol CH}_4} \]

3. Amount of \( \text{H}_2\text{O} \) in mol
   multiply by the molar mass of \( \text{H}_2\text{O} \)
   \[ \frac{18.02 \text{ g H}_2\text{O}}{1 \text{ mol H}_2\text{O}} \]

4. Mass of \( \text{H}_2\text{O} \) in g
   \[ \frac{1 \text{ mol CH}_4}{16.05 \text{ g CH}_4} \times \frac{2 \text{ mol H}_2\text{O}}{1 \text{ mol CH}_4} \times \frac{18.02 \text{ g H}_2\text{O}}{1 \text{ mol H}_2\text{O}} = \text{g H}_2\text{O} \]
Problem Solving continued

**COMPUTE**

\[
500. \text{ g CH}_4 \times \frac{1 \text{ mol CH}_4}{16.05 \text{ g CH}_4} \times \frac{2 \text{ mol H}_2\text{O}}{1 \text{ mol CH}_4} \times \frac{18.02 \text{ g H}_2\text{O}}{1 \text{ mol H}_2\text{O}} = 1.12 \times 10^3 \text{ g H}_2\text{O}
\]

**EVALUATE**

Are the units correct?
Yes; mass of H\textsubscript{2}O was required, and units canceled to give grams H\textsubscript{2}O.

Is the number of significant figures correct?
Yes; three significant figures is correct because the mass of CH\textsubscript{4} was given to three significant figures.

Is the answer reasonable?
Yes; CH\textsubscript{4} and H\textsubscript{2}O have similar molar masses, and twice as many moles of H\textsubscript{2}O are produced as moles CH\textsubscript{4} burned. So, you would expect to get a little more than 1000 g of H\textsubscript{2}O.

**Practice**

1. Calculate the mass of silver bromide produced from 22.5 g of silver nitrate in the following reaction:

\[
2\text{AgNO}_3(aq) + \text{MgBr}_2(aq) \rightarrow 2\text{AgBr}(s) + \text{Mg(NO}_3)_2(aq)
\]

ans: 24.9 g AgBr

2. What mass of acetylene, C\textsubscript{2}H\textsubscript{2}, will be produced from the reaction of 90. g of calcium carbide, CaC\textsubscript{2}, with water in the following reaction?

\[
\text{CaC}_2(s) + 2\text{H}_2\text{O}(l) \rightarrow \text{C}_2\text{H}_2(g) + \text{Ca(OH}}_2(s)
\]

ans: 37 g C\textsubscript{2}H\textsubscript{2}

3. Chlorine gas can be produced in the laboratory by adding concentrated hydrochloric acid to manganese(IV) oxide in the following reaction:

\[
\text{MnO}_2(s) + 4\text{HCl}(aq) \rightarrow \text{MnCl}_2(aq) + 2\text{H}_2\text{O}(l) + \text{Cl}_2(g)
\]

a. Calculate the mass of MnO\textsubscript{2} needed to produce 25.0 g of Cl\textsubscript{2}. ans: 30.7 g MnO\textsubscript{2}

b. What mass of MnCl\textsubscript{2} is produced when 0.091 g of Cl\textsubscript{2} is generated? ans: 0.16 g MnCl\textsubscript{2}
Problem Solving continued

Additional Problems

1. How many moles of ammonium sulfate can be made from the reaction of 30.0 mol of NH₃ with H₂SO₄ according to the following equation?
   \[ 2\text{NH}_3 + \text{H}_2\text{SO}_4 \rightarrow (\text{NH}_4)_2\text{SO}_4 \]

2. In a very violent reaction called a thermite reaction, aluminum metal reacts with iron(III) oxide to form iron metal and aluminum oxide according to the following equation:
   \[ \text{Fe}_2\text{O}_3 + 2\text{Al} \rightarrow 2\text{Fe} + \text{Al}_2\text{O}_3 \]
   a. What mass of Al will react with 150 g of Fe₂O₃?
   b. If 0.905 mol Al₂O₃ is produced in the reaction, what mass of Fe is produced?
   c. How many moles of Fe₂O₃ will react with 99.0 g of Al?

3. As you saw in Sample Problem 1, the reaction \( \text{N}_2(g) + 3\text{H}_2(g) \rightarrow 2\text{NH}_3(g) \) is used to produce ammonia commercially. If 1.40 g of N₂ are used in the reaction, how many grams of H₂ will be needed?

4. What mass of sulfuric acid, H₂SO₄, is required to react with 1.27 g of potassium hydroxide, KOH? The products of this reaction are potassium sulfate and water.

5. Ammonium hydrogen phosphate, \((\text{NH}_4)_2\text{HPO}_4\), a common fertilizer, is made from reacting phosphoric acid, H₃PO₄, with ammonia.
   a. Write the equation for this reaction.
   b. If 10.00 g of ammonia react, how many moles of fertilizer will be produced?
   c. What mass of ammonia will react with 2800 kg of H₃PO₄?

6. The following reaction shows the synthesis of zinc citrate, a ingredient in toothpaste, from zinc carbonate and citric acid.
   \[ 3\text{ZnCO}_3(s) + 2\text{C}_6\text{H}_8\text{O}_7(aq) \rightarrow \text{Zn}_3\text{(C}_6\text{H}_5\text{O}_7)_2(aq) + 3\text{H}_2\text{O}(l) + 3\text{CO}_2(g) \]
   a. How many moles of ZnCO₃ and C₆H₈O₇ are required to produce 30.0 mol of Zn₃(C₆H₅O₇)₂?
   b. What quantities, in kilograms, of H₂O and CO₂ are produced by the reaction of 500. mol of citric acid?

7. Methyl butanoate, an oily substance with a strong fruity fragrance, can be made by reacting butanoic acid with methanol according to the following equation:
   \[ \text{C}_3\text{H}_7\text{COOH} + \text{CH}_3\text{OH} \rightarrow \text{C}_3\text{H}_7\text{COOCH}_3 + \text{H}_2\text{O} \]
   a. What mass of methyl butanoate is produced from the reaction of 52.5 g of butanoic acid?
   b. In order to purify methyl butanoate, water must be removed. What mass of water is produced from the reaction of 5800. g of methanol?
8. Ammonium nitrate decomposes to yield nitrogen gas, water, and oxygen gas in the following reaction:

$$2\text{NH}_4\text{NO}_3 \rightarrow 2\text{N}_2 + \text{O}_2 + 4\text{H}_2\text{O}$$

a. How many moles of nitrogen gas are produced when 36.0 g of NH$_4$NO$_3$ reacts?

b. If 7.35 mol of H$_2$O are produced in this reaction, what mass of NH$_4$NO$_3$ reacted?

9. Lead(II) nitrate reacts with potassium iodide to produce lead(II) iodide and potassium nitrate. If 1.23 mg of lead nitrate are consumed, what is the mass of the potassium nitrate produced?

10. A car battery produces electrical energy with the following chemical reaction:

$$\text{Pb}(s) + \text{PbO}_2(s) + 2\text{H}_2\text{SO}_4(aq) \rightarrow 2\text{PbSO}_4(s) + 2\text{H}_2\text{O}(l)$$

If the battery loses 0.34 kg of lead in this reaction, how many moles of lead(II) sulfate are produced?

11. In a space shuttle, the CO$_2$ that the crew exhales is removed from the air by a reaction within canisters of lithium hydroxide. On average, each astronaut exhales about 20.0 mol of CO$_2$ daily. What mass of water will be produced when this amount reacts with LiOH? The other product of the reaction is Li$_2$CO$_3$.

12. Water is sometimes removed from the products of a reaction by placing them in a closed container with excess P$_4$O$_{10}$. Water is absorbed by the following reaction:

$$\text{P}_4\text{O}_{10} + 6\text{H}_2\text{O} \rightarrow 4\text{H}_3\text{PO}_4$$

a. What mass of water can be absorbed by $1.00 \times 10^2$ g of P$_4$O$_{10}$?

b. If the P$_4$O$_{10}$ in the container absorbs 0.614 mol of water, what mass of H$_3$PO$_4$ is produced?

c. If the mass of the container of P$_4$O$_{10}$ increases from 56.64 g to 63.70 g, how many moles of water are absorbed?

13. Ethanol, C$_2$H$_5$OH, is considered a clean fuel because it burns in oxygen to produce carbon dioxide and water with few trace pollutants. If 95.0 g of H$_2$O are produced during the combustion of ethanol, how many grams of ethanol were present at the beginning of the reaction?

14. Sulfur dioxide is one of the major contributors to acid rain. Sulfur dioxide can react with oxygen and water in the atmosphere to form sulfuric acid, as shown in the following equation:

$$2\text{H}_2\text{O}(l) + \text{O}_2(g) + 2\text{SO}_2(g) \rightarrow 2\text{H}_2\text{SO}_4(aq)$$

If 50.0 g of sulfur dioxide from pollutants reacts with water and oxygen found in the air, how many grams of sulfuric acid can be produced? How many grams of oxygen are used in the process?
15. When heated, sodium bicarbonate, NaHCO₃, decomposes into sodium carbonate, Na₂CO₃, water, and carbon dioxide. If 5.00 g of NaHCO₃ decomposes, what is the mass of the carbon dioxide produced?

16. A reaction between hydrazine, N₂H₄, and dinitrogen tetroxide, N₂O₄, has been used to launch rockets into space. The reaction produces nitrogen gas and water vapor.
   a. Write a balanced chemical equation for this reaction.
   b. What is the mole ratio of N₂O₄ to N₂?
   c. How many moles of N₂ will be produced if 20 000 mol of N₂H₄ are used by a rocket?
   d. How many grams of H₂O are made when 450. kg of N₂O₄ are consumed?

17. Joseph Priestley is credited with the discovery of oxygen. He produced O₂ by heating mercury(II) oxide, HgO, to decompose it into its elements. How many moles of oxygen could Priestley have produced if he had decomposed 517.84 g of mercury oxide?

18. Iron(III) chloride, FeCl₃, can be made by the reaction of iron with chlorine gas. How much iron, in grams, will be needed to completely react with 58.0 g of Cl₂?

19. Sodium sulfide and cadmium nitrate undergo a double-displacement reaction, as shown by the following equation:
   \[ \text{Na}_2\text{S} + \text{Cd(NO}_3\text{)}_2 \rightarrow 2\text{NaNO}_3 + \text{CdS} \]
   What is the mass, in milligrams, of cadmium sulfide that can be made from 5.00 mg of sodium sulfide?

20. Potassium permanganate and glycerin react explosively according to the following equation:
   \[ 14\text{KMnO}_4 + 4\text{C}_3\text{H}_5(\text{OH})_3 \rightarrow 7\text{K}_2\text{CO}_3 + 7\text{Mn}_2\text{O}_3 + 5\text{CO}_2 + 16\text{H}_2\text{O} \]
   a. How many moles of carbon dioxide can be produced from 4.44 mol of KMnO₄?
   b. If 5.21 g of H₂O are produced, how many moles of glycerin, C₃H₅(OH)₃, were used?
   c. If 3.39 mol of potassium carbonate are made, how many grams of manganese(III) oxide are also made?
   d. How many grams of glycerin will be needed to react with 50.0 g of KMnO₄? How many grams of CO₂ will be produced in the same reaction?

21. Calcium carbonate found in limestone and marble reacts with hydrochloric acid to form calcium chloride, carbon dioxide, and water according to the following equation:
   \[ \text{CaCO}_3(s) + 2\text{HCl}(aq) \rightarrow \text{CaCl}_2(aq) + \text{CO}_2(g) + \text{H}_2\text{O}(l) \]
   a. What mass of HCl will be needed to produce 5.00 \( \times 10^3 \) kg of CaCl₂?
   b. What mass of CO₂ could be produced from the reaction of 750 g of CaCO₃?
22. The fuel used to power the booster rockets on the space shuttle is a mixture of aluminum metal and ammonium perchlorate. The following balanced equation represents the reaction of these two ingredients:

\[ 3\text{Al(s)} + 3\text{NH}_4\text{ClO}_4(s) \rightarrow \text{Al}_2\text{O}_3(s) + \text{AlCl}_3(g) + 3\text{NO}(g) + 6\text{H}_2\text{O}(g) \]

a. If \(1.50 \times 10^5\) g of Al react, what mass of NH\(_4\)ClO\(_4\), in grams, is required?
b. If aluminum reacts with 620 kg of NH\(_4\)ClO\(_4\), what mass of nitrogen monoxide is produced?

23. Phosphoric acid is typically produced by the action of sulfuric acid on rock that has a high content of calcium phosphate according to the following equation:

\[ 3\text{H}_2\text{SO}_4 + \text{Ca}_3(\text{PO}_4)_2 + 6\text{H}_2\text{O} \rightarrow 3[\text{CaSO}_4 \cdot 2\text{H}_2\text{O}] + 2\text{H}_3\text{PO}_4 \]

a. If \(2.50 \times 10^5\) kg of H\(_2\)SO\(_4\) react, how many moles of H\(_3\)PO\(_4\) can be made?
b. What mass of calcium sulfate dihydrate is produced by the reaction of 400 kg of calcium phosphate?
c. If the rock being used contains 78.8% Ca\(_3\)(PO\(_4\))\(_2\), how many metric tons of H\(_3\)PO\(_4\) can be produced from 68 metric tons of rock?

24. Rusting of iron occurs in the presence of moisture according to the following equation:

\[ 4\text{Fe(s)} + 3\text{O}_2(g) \rightarrow 2\text{Fe}_2\text{O}_3(s) \]

Suppose that 3.19% of a heap of steel scrap with a mass of 1650 kg rusts in a year. What mass will the heap have after one year of rusting?
5. a. C₆H₁₂S₃  
   b. C₈H₁₆O₄  
   c. C₄H₆O₄  
   d. C₁₂H₁₀O₆

6. a. C₄H₄O₄  
   b. C₄H₈O₂  
   c. C₉H₁₂O₃

7. K₂S₂O₅, potassium metabisulfite

8. Pb₃O₄

9. Cr₂S₃O₁₂ or Cr₂(SO₄)₃, chromium(III) sulfate

10. C₉H₆O₄

11. C₅H₉N₃, the empirical formula and the molecular formula are the same

12. The molecular formulas of the compounds are different multiples of the same empirical formula. (FYI: The first could be acetic acid, C₂H₄O₂, and the second could be glucose, C₆H₁₂O₆, or some other simple sugar.)

**Stoichiometry**

**STOICHIOMETRY**

1. 15.0 mol (NH₄)₂SO₄

2. a. 51 g Al  
   b. 101 g Fe  
   c. 1.83 mol Fe₂O₃

3. 0.303 g H₂

4. H₂SO₄ + 2KOH → K₂SO₄ + 2H₂O; 1.11 g H₂SO₄

5. a. H₃PO₄ + 2NH₃ → (NH₄)₂HPO₄  
   b. 0.293 mol (NH₄)₂HPO₄  
   c. 970 kg NH₃

6. a. 90.0 mol ZnCO₃; 60.0 mol C₆H₈O₇  
   b. 13.5 kg H₂O; 33.0 kg CO₂

7. a. 60.9 g methyl butanoate  
   b. 3261 g H₂O

8. a. 0.450 mol N₂  
   b. 294 g NH₄NO₃

9. Pb(NO₃)₂ + 2KI → PbI₂ + 2KNO₃; 0.751 mg KNO₃

10. 3.3 mol PbSO₄

11. 2LiOH + CO₂ → H₂O + Li₂CO₃; 360 g H₂O

12. a. 38.1 g H₂O  
   b. 40.1 g H₂PO₄

13. C₂H₂OH + 3O₂ → 2CO₂ + 3H₂O; 81.0 g C₂H₂OH

14. 76.5 g H₂SO₄; 12.5 g O₂

15. 2NaHCO₃ → Na₂CO₃ + H₂O + CO₂; 1.31 g CO₂

16. a. 2N₂H₄ + N₂O₄ → 3N₂ + 4H₂O  
   b. 1 mol N₂O₄ to 3 mol N₂  
   c. 30 000 mol N₂  
   d. 3.52 × 10⁶ g H₂O

17. 2HgO(s) → 2Hg(l) + O₂(g); 1.1954 mol O₂

18. 2Fe + 3Cl₂ → 2FeCl₃; 30.5 g Fe

19. 9.26 mg CdS

20. a. 1.59 mol CO₂  
   b. 0.0723 mol C₃H₅(OH)₃  
   c. 535 g Mn₂O₃

21. a. 3.29 × 10² kg of HCl  
   b. 330 g CO₂ (g)

22. a. 6.53 × 10⁵ g NH₄ClO₄  
   b. 160 kg NO(g)

23. a. 1.70 × 10⁶ mol H₃PO₄  
   b. 666 kg of CaSO₄·2H₂O  
   c. 34 metric tons of H₃PO₄

24. 1670 kg

**LIMITING REACTANTS**

1. 2ZnS + 3O₂ → 2ZnO + 2SO₂; ZnS is limiting

2. a. Al is limiting  
   b. 4.25 × 10⁻³ mol Al₂O₃  
   c. O₂ is limiting

3. a. CuS is limiting  
   b. 15.6 g CuO

4. Fe is limiting; 0.158 mol Cu

5. 54 g Ba(NO₃)₂

6. a. 38 g Br₂  
   b. 510 g I₂

7. a. Ni is in excess  
   b. 60.2 g Ni(NO₃)₂

8. CS₂(g) + 3O₂(g) → 2SO₄(g) + CO₂(g)  
   0.80 mol O₂ remain

9. a. 0.84 g Hg(NH₂)Cl  
   b. 0.84 g

10. a. 2Al(s) + 2NaOH(aq) + 2H₂O(l) → 2NaAlO₂(aq) + 3H₂(g)  
   b. NaOH is limiting; 0.56 mol H₂  
   c. Al should be limiting because you would not want aluminum metal remaining in the drain.

11. a. 0.0422 mol Cu; 0.169 mol HNO₃  
   b. Cu is in excess

12. a. 2.90 mol NO; 4.35 mol H₂O
   b. NH₃ is limiting  
   c. NH₃ is limiting; 1.53 × 10³ kg NO