12.3

1 FOCUS

Objectives

12.3.1 Identify the limiting reagent in a reaction.

12.3.2 Calculate theoretical yield, actual yield, or percent yield given appropriate information.

Guide for Reading

Build Vocabulary L2

LINCS Have students use the LINCS strategy for the terms *theoretical yield, actual yield, and percent yield.* Students should **L**ist the parts of a term they know; **I**magine a picture of the term; **N**ote a "sound-alike word" for the term; **C**onnect the terms; and **S**elf-test the terms.

Reading Strategy L2

Compare and Contrast Compare and contrast the terms *limiting reagent* and *excess reagent.*

2 INSTRUCT

Connecting to Your World

Have students study the photograph and read the text. Ask, **If the carpenter decided to construct a built-in table using two legs for support, what would limit the number of tables constructed?** *(tabletops)* **What and how many unused parts would remain** *(3 legs)*

Limiting and Excess Reagents

Use Visuals L1

Figure 12.9 Ask, **Where else do you see examples of processes or activities being "limited" on an everyday basis?** *(Acceptable answers include the number of people you can fit into a car, and the number of cookies that can be made from a given amount of dough.)*

12.3 Limiting Reagent and Percent Yield

Guide for Reading

Key Concepts

- How is the amount of product in a reaction affected by an insufficient quantity of any of the reactants?
- What does the percent yield of a reaction measure?

Vocabulary

limiting reagent
excess reagent
theoretical yield
actual yield
percent yield

Reading Strategy

Building Vocabulary After you have read the section, explain the differences among *theoretical yield, actual yield,* and *percent yield.*

Connecting to Your World If a carpenter had two tabletops and seven table legs, he would have difficulty building more than one functional four-legged table. The first table would require four of the legs, leaving just three legs for the second table. In this case, the number of table legs is the limiting factor in the construction of four-legged tables. A similar concept applies in chemistry. The amount of product made in a chemical reaction may be limited by the amount of one or more of the reactants.

Limiting and Excess Reagents

Many cooks follow a recipe when making a new dish. They know that sufficient quantities of all the ingredients must be available. Suppose, for example, that you are preparing to make lasagna and you have more than enough meat, tomato sauce, ricotta cheese, eggs, mozzarella cheese, spinach, and seasoning on hand. However, you have only half a box of lasagna noodles. The amount of lasagna you can make will be limited by the quantity of noodles you have. Thus, the noodles are the limiting ingredient in this baking venture. Figure 12.9 illustrates another example of a limiting ingredient in the kitchen. A chemist often faces a similar situation. **In a chemical reaction, an insufficient quantity of any of the reactants will limit the amount of product that forms.**

Figure 12.9 The amount of product is determined by the quantity of the limiting reagent. In this example, the rolls are the limiting reagent. No matter how much of the other ingredients you have, with two rolls you can make only two sandwiches.

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 12.3
- **Core Teaching Resources,** Section 12.3 Review, Interpreting Graphics
- **Transparencies,** T133–T138
- **Laboratory Manual,** Lab 20

Technology

- **Interactive Textbook with ChemASAP,** Animation 13, Problem-Solving 12.25, 12.28, 12.29, 12.31, Assessment 12.3
- **Go Online,** Section 12.3

368 Chapter 12

Chemical Equations

	$N_2(g)$	+	$3H_2(g)$	→	$2NH_3(g)$
"Microscopic recipe"	1 molecule N_2	+	3 molecules H_2	→	2 molecules NH_3
"Macroscopic recipe"	1 mol N_2	+	3 mol H_2	→	2 mol NH_3

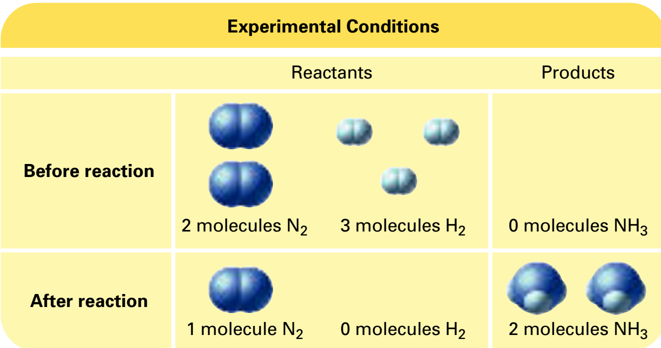


Figure 12.10 The "recipe" calls for 3 molecules of H_2 for every 1 molecule of N_2. In this particular experiment, H_2 is the limiting reagent and N_2 is in excess. **Inferring** ***How would the amount of products formed change if you started with four molecules of N_2 and three molecules of H_2?***

As you know, a balanced chemical equation is a chemist's recipe. You can interpret the recipe on a microscopic scale (interacting particles) or on a macroscopic scale (interacting moles). The coefficients used to write the balanced equation give both the ratio of representative particles and the mole ratio. Recall the equation for the preparation of ammonia:

$$N_2(g) + 3H_2(g) \longrightarrow 2NH_3(g)$$

When one molecule (mole) of N_2 reacts with three molecules (moles) of H_2, two molecules (moles) of NH_3 are produced. What would happen if two molecules (moles) of N_2 reacted with three molecules (moles) of H_2? Would more than two molecules (moles) of NH_3 be formed? Figure 12.10 shows both the particle and the mole interpretations of this problem.

Before the reaction takes place, nitrogen and hydrogen are present in a 2:3 molecule (mole) ratio. The reaction takes place according to the balanced equation. One molecule (mole) of N_2 reacts with three molecules (moles) of H_2 to produce two molecules (moles) of NH_3. At this point, all the hydrogen has been used up, and the reaction stops. One molecule (mole) of unreacted nitrogen is left in addition to the two molecules (moles) of NH_3 that have been produced by the reaction.

In this reaction, only the hydrogen is completely used up. It is the **limiting reagent,** or the reagent that determines the amount of product that can be formed by a reaction. The reaction occurs only until the limiting reagent is used up. By contrast, the reactant that is not completely used up in a reaction is called the **excess reagent.** In this example, nitrogen is the excess reagent because some nitrogen will remain unreacted.

Sometimes in stoichiometric problems, the given quantities of reactants are expressed in units other than moles. In such cases, the first step in the solution is to convert each reactant to moles. Then the limiting reagent can be identified. The amount of product formed in a reaction can be determined from the given amount of limiting reagent.

Checkpoint ***How do limiting and excess reagents differ?***

Go Online NSTA SCILINKS
For: Links on Hydrogen
Visit: www.SciLinks.org
Web Code: cdn-1123

Interactive Textbook
Animation 13 Apply the limiting reagent concept to the production of iron from iron ore.
with **ChemASAP**

TEACHER Demo

Limiting Factor L2

Purpose Students model the concept of a limiting reagent.

Materials 15 plastic bottles, 30 plastic caps to fit the bottles, 6 containers to hold 5 caps each

Procedure Before the demonstration, place five caps in each container and put them out of the sight of the students. Set out all 15 plastic bottles. Bring out one container of caps. Ask, **How many closed plastic bottles can we have?** *(5)* **What limits the number?** *(caps)* Bring out another container of caps. Again, ask the students what will happen. Continue bringing out caps and matching them to the bottles.

Expected Outcome With two containers of caps, student should indicate that the caps are the limiting factor. With three containers, students should realize that there is a one-to-one correspondence and therefore no limiting factor. (Or, students may argue that both the bottles and caps are equally limiting factors.) With the remaining containers, the caps are in excess and students should indicate that the bottles are the limiting factor.

Go Online NSTA SCILINKS
Download a worksheet on **Hydrogen** for students to complete and find additional support for NSTA SciLinks.

Differentiated Instruction

Less Proficient Readers L1

Help students understand the concept of a limiting reagent by comparing it to everyday situations. For example, suppose a person is planning a dinner party. He has 6 glasses, 8 plates, and 4 chairs. How many people can he invite? Or, how many letters can you send if you have 24 pieces of stationery, 12 envelopes, and 10 stamps?

Answers to...

Figure 12.10 The amount would remain the same; two molecules of NH_3 would form.

Checkpoint The limiting reagent is completely used up in a reaction. The excess reagent is not completely used up; some of it remains after the reaction takes place.

Discuss

L2

Write the balanced chemical equation for the following reaction on the board: $2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$. Ask a series of questions that require students to predict the amount of product formed based on molar quantities of reactant supplied by you. Use small whole numbers that students can easily manipulate without calculators. As students solve the problems, create a list of molar quantities under each reactant and product showing how they are related for each set of conditions. In each case, ask students to state which reactant is the limiting reagent and circle the value in the list to designate it as the limiting quantity.

Sample Problem 12.7

Answers

25. O_2 is the limiting reagent.
26. HCl is the limiting reagent.

Practice Problems Plus

L2

Phosphoric acid reacts with sodium hydroxide according to the equation:

$$H_3PO_4(aq) + 3NaOH(aq) \rightarrow Na_3PO_4(aq) + 3H_2O(l)$$

If 1.75 mol H_3PO_4 is made to react with 5.00 mol NaOH, identify the limiting reagent. *(5.25 mol NaOH required; NaOH is the limiting reagent)*

Math Handbook

For a math refresher and practice, direct students to dimensional analysis, page R66.

Copper(I) sulfide (Cu_2S)

SAMPLE PROBLEM 12.7

Determining the Limiting Reagent in a Reaction

Copper reacts with sulfur to form copper(I) sulfide according to the following balanced equation.

$$2Cu(s) + S(s) \longrightarrow Cu_2S(s)$$

What is the limiting reagent when 80.0 g Cu reacts with 25.0 g S?

1 Analyze ***List the knowns and the unknown.***

Knowns
- mass of copper = 80.0 g Cu
- mass of sulfur = 25.0 g S

Unknown
- limiting reagent = ?

The number of moles of each reactant must first be found:

$$g\ Cu \longrightarrow mol\ Cu$$

$$g\ S \longrightarrow mol\ S$$

The balanced equation is used to calculate the number of moles of one reactant needed to react with the given amount of the other reactant:

$$mol\ Cu \longrightarrow mol\ S$$

The mole ratio relating mol S to mol Cu from the balanced chemical equation is 1 mol S/2 mol Cu.

2 Calculate ***Solve for the unknown.***

$$80.0\ g\ \cancel{Cu} \times \frac{1\ mol\ Cu}{63.5\ g\ \cancel{Cu}} = 1.26\ mol\ Cu$$

$$25.0\ g\ \cancel{S} \times \frac{1\ mol\ S}{32.1\ g\ \cancel{S}} = 0.779\ mol\ S$$

$$\underbrace{1.26\ \cancel{mol\ Cu}}_{\text{Given quantity}} \times \underbrace{\frac{1\ mol\ S}{2\ \cancel{mol\ Cu}}}_{\text{Mole ratio}} = \underbrace{0.630\ mol\ S}_{\text{Needed amount}}$$

Comparing the amount of sulfur needed (0.630 mol S) with the given amount (0.779 mol S) indicates that sulfur is in excess. Thus copper is the limiting reagent.

3 Evaluate ***Do the results make sense?***

Since the ratio of the given mol Cu to mol S was less than the ratio (2:1) from the balanced equation, copper should be the limiting reagent.

Practice Problems

25. The equation for the complete combustion of ethene (C_2H_4) is

$$C_2H_4(g) + 3O_2(g) \longrightarrow 2CO_2(g) + 2H_2O(g)$$

If 2.70 mol C_2H_4 is reacted with 6.30 mol O_2, identify the limiting reagent.

26. Hydrogen gas can be produced by the reaction of magnesium metal with hydrochloric acid.

$$Mg(s) + 2HCl(aq) \longrightarrow MgCl_2(aq) + H_2(g)$$

Identify the limiting reagent when 6.00 g HCl reacts with 5.00 g Mg.

Math Handbook

For help with dimensional analysis, go to page R66.

Interactive Textbook

Problem-Solving 12.25 Solve Problem 25 with the help of an interactive guided tutorial.

with ChemASAP

In Sample Problem 12.7, you may have noticed that even though the mass of copper used in the reaction is greater than the mass of sulfur, copper is the limiting reagent. The reactant that is present in the smaller amount by mass or volume is not necessarily the limiting reagent.

SAMPLE PROBLEM 12.8

Using a Limiting Reagent to Find the Quantity of a Product

What is the maximum number of grams of Cu_2S that can be formed when 80.0 g Cu reacts with 25.0 g S?

$$2Cu(s) + S(s) \longrightarrow Cu_2S(s)$$

1 **Analyze** *List the knowns and the unknown.*

Knowns

- limiting reagent = 1.26 mol Cu (from Sample Problem 12.7)
- 1 mol Cu_2S = 159.1 g Cu_2S (molar mass)

Unknown

- mass copper(I) sulfide = ? g Cu_2S

The limiting reagent, which was determined in the previous sample problem, is used to calculate the maximum amount of Cu_2S formed:

$$\text{mol Cu} \longrightarrow \text{mol } Cu_2S \longrightarrow \text{g } Cu_2S$$

2 The equation yields the appropriate mole ratio: 1 mol Cu_2S/2 mol Cu.

Calculate *Solve for the unknown.*

$$1.26\ \cancel{\text{mol Cu}} \times \frac{1\ \cancel{\text{mol } Cu_2S}}{2\ \cancel{\text{mol Cu}}} \times \frac{159.1\ \text{g } Cu_2S}{1\ \cancel{\text{mol } Cu_2S}} = 1.00 \times 10^2\ \text{g } Cu_2S$$

The given quantity of copper, 80.0 g, could have been used for this step instead of the moles of copper, which were calculated in Sample Problem 12.7.

3 **Evaluate** *Do the results make sense?*

Copper is the limiting reagent in this reaction. The maximum number of grams of Cu_2S produced should be more than the amount of copper that initially reacted because copper is combining with sulfur. However, the mass of Cu_2S produced should be less than the total mass of the reactants (105.0 g) because sulfur was in excess.

Practice Problems

27. The equation below shows the incomplete combustion of ethene.

$$C_2H_4(g) + 2O_2(g) \longrightarrow 2CO(g) + 2H_2O(g)$$

If 2.70 mol C_2H_4 is reacted with 6.30 mol O_2,

a. identify the limiting reagent.
b. calculate the moles of water produced.

28. The heat from an acetylene torch is produced by burning acetylene (C_2H_2) in oxygen.

$$2C_2H_2(g) + 5O_2(g) \longrightarrow 4CO_2(g) + 2H_2O(g)$$

How many grams of water can be produced by the reaction of 2.40 mol C_2H_2 with 7.40 mol O_2?

Interactive Textbook

Problem-Solving 12.28 Solve Problem 28 with the help of an interactive guided tutorial.

with ChemASAP

Relate L2

Have students reread the Inquiry Activity. Ask, **What is the maximum number of product molecules that can be formed using the procedure described in the activity?** *(Given that (a) one molecule of* M_2 *reacts with three molecules of* C_2*, (b) there are only ten molecules of each reactant available, and (c) fifteen molecules are chosen, a maximum of three* M_2 *molecules can react with nine* C_2 *molecules to form a total of six* MC_3 *molecules.)*

Sample Problem 12.8

Answers

27. a. 5.40 mol O_2 required; C_2H_4 is the limiting reactant.
b. 5.40 mol H_2O

28. 43.2 g H_2O

Practice Problems Plus L2

Chapter 12 Assessment problem 51 is related to Sample Problem 12.8.

Facts and Figures

Comparative Torch Temperatures

- Acetylene welding torches produce flame temperature of 3300–3400°C.
- Propane torches reach flame temperatures of about 1400°C.
- The flame of a match has a temperature range of 600–800°C.

Quick LAB

Limiting Reagents **L2**

Objective After completing this activity, students will be able to
- compare the amount of hydrogen gas produced from the reaction of magnesium and hydrochloric acid with the amounts of magnesium.
- infer the limiting reagent in reactions of magnesium and hydrochloric acid.

Skills Focus Observing, measuring, calculating

Prep Time 15 minutes

Materials graduated cylinders, mass balances, 250-mL Erlenmeyer flasks, rubber balloons, magnesium ribbons, 1.0*M* hydrochloric acid

Class Time 20 minutes

Safety The balloons contain hydrogen gas and should be kept away from heat and open flames during and after the experiment. Caution students about the corrosive nature of HCl. Students should wear safety glasses and aprons. Once the reaction in a flask is complete, carefully remove the balloon. Disperse the gas in a fume hood or outside. Neutralize remaining HCl(*aq*) with baking soda before flushing down the drain.

Teaching Tips

- Have students carefully balance the equation for the reaction and then look at the mole ratio from the balanced equation and the molar amounts of the two reactants present before they make their prediction in Step 4.

Expected Outcome The approximate volumes of the balloons are 0.60 g Mg, 0.5 L H_2; 1.2 g Mg, 1 L H_2; 2.4 g Mg, 1 L H_2.

Analyze and Conclude

1. Those students who failed to balance the equation, obtain the mole ratio, and compare the molar amounts of reactants, likely predicted a doubling of the volume with each doubling of the mass of magnesium.

Quick LAB

Limiting Reagents

Purpose

To illustrate the concept of a limiting reagent in a chemical reaction.

Materials

- graduated cylinder
- balance
- 3 250-mL Erlenmeyer flasks
- 3 rubber balloons
- 4.2 g magnesium ribbon
- 300 mL 1.0*M* hydrochloric acid

Procedure

1. Add 100 mL of the hydrochloric acid solution to each flask.
2. Weigh out 0.6 g, 1.2 g, and 2.4 g of magnesium ribbon, and place each sample into its own balloon.
3. Stretch the end of each balloon over the mouth of each flask. Do not allow the magnesium ribbon in the balloon to fall into the flask.
4. Magnesium reacts with hydrochloric acid to form hydrogen gas. When you mix the magnesium with the hydrochloric acid in the next step, you will generate a certain volume of hydrogen gas. How do you think the volume of hydrogen produced in each flask will compare?
5. Lift up on each balloon and shake the magnesium into each flask. Observe the volume of gas produced until the reaction in each flask is completed.

Analyze and Conclude

1. How did the volumes of hydrogen gas produced, as measured by the size of the balloons, compare? Did the results agree with your prediction?
2. Write a balanced equation for the reaction you observed.
3. The 100 mL of hydrochloric acid contained 0.10 mol HCl. Show by calculation why the balloon with 1.2 g Mg inflated to about twice the size of the balloon with 0.60 g Mg.
4. Show by calculation why the balloons with 1.2 g and 2.4 g Mg inflated to approximately the same volume. What was the limiting reagent when 2.4 g Mg was added to the acid?

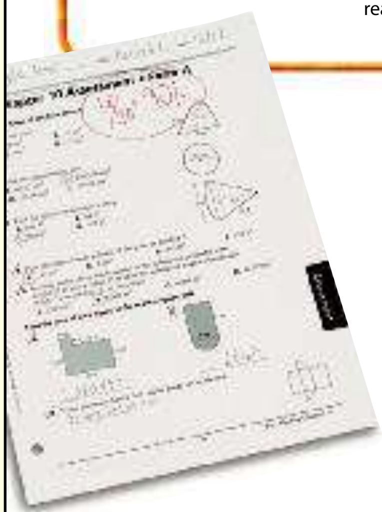


Figure 12.11 Calculating the ratio of the number of correct answers to the number of questions on the exam is a measure of how well the student performed on the exam.

Percent Yield

In theory, when a teacher gives an exam to the class, every student should get a grade of 100%. This generally does not occur, as shown in Figure 12.11. Instead, the performance of the class is usually spread over a range of grades. Your exam grade, expressed as a percentage, is a ratio of two items. The first item is the number of questions you answered correctly. The second is the total number of questions. The grade compares how well you performed with how well you could have performed if you had answered all the questions correctly. Chemists perform similar calculations in the laboratory when the product from a chemical reaction is less than expected, based on the balanced chemical equation.

When an equation is used to calculate the amount of product that will form during a reaction, the calculated value represents the theoretical yield. The **theoretical yield** is the maximum amount of product that could be formed from given amounts of reactants. In contrast, the amount of product that actually forms when the reaction is carried out in the laboratory is called the **actual yield.** The **percent yield** is the ratio of the actual yield to the theoretical yield expressed as a percent.

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

2. $Mg + 2HCl \rightarrow MgCl_2 + H_2$
3. A mass of 0.60 g Mg is 0.025 mol Mg. Because Mg and HCl react in a 1:2 mol ratio, 0.10 mol HCl is in excess and Mg is limiting. According to the balanced equation, 0.025 mol Mg should produce 0.025 mol H_2. A mass of 1.2 g Mg is 0.050 mol Mg. According to the balanced equation, 0.050 mol Mg will react with 0.1 mol HCl to produce 0.05 mol H_2.
4. A mass of 2.4 g Mg is 0.10 mol Mg. Because there is only 0.1 mol HCl in the flask and, according to the equation, 0.20 mol HCl is needed to react with 0.10 mol Mg, HCl is limiting. Therefore, only 0.05 mol H_2 is produced.

For Enrichment **L3**

Ask, **What other clue could be used to determine if HCl was the limiting reagent?** *(If HCl were the limiting reagent, remaining magnesium metal would be present after the reaction.)*

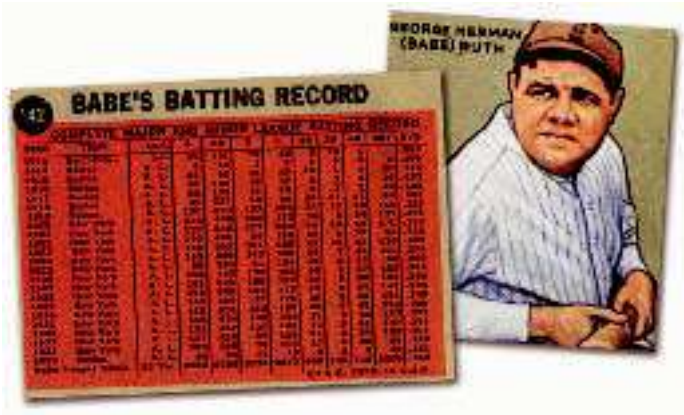


Figure 12.12 A batting average is actually a percent yield.

Because the actual yield of a chemical reaction is often less than the theoretical yield, the percent yield is often less than 100%. **The percent yield is a measure of the efficiency of a reaction carried out in the laboratory.** This is similar to an exam score measuring your efficiency of learning, or a batting average measuring your efficiency of hitting a baseball.

A percent yield should not normally be larger than 100%. Many factors cause percent yields to be less than 100%. Reactions do not always go to completion; when this occurs, less than the calculated amount of product is formed. Impure reactants and competing side reactions may cause unwanted products to form. Actual yield can also be lower than the theoretical yield due to a loss of product during filtration or in transferring between containers. Moreover, if reactants or products have not been carefully measured, a percent yield of 100% is unlikely.

An actual yield is an experimental value. Figure 12.13 shows a typical laboratory procedure for determining the actual yield of a product of a decomposition reaction. For reactions in which percent yields have been determined, you can calculate and therefore predict an actual yield if the reaction conditions remain the same.

Checkpoint ***What factors can cause the actual yield to be less than the theoretical yield?***

Figure 12.13 Sodium hydrogen carbonate ($NaHCO_3$) will decompose when heated. **a** The mass of $NaHCO_3$, the reactant, is measured. **b** The reactant is heated. **c** The mass of one of the products, sodium carbonate (Na_2CO_3), the actual yield, is measured. The percent yield is calculated once the actual yield is determined. **Predicting** ***What are the other products of this reaction?***

Percent Yield

CLASS Activity

Actual Yield and Heat

Purpose Students assess actual yield of a reaction based on temperature changes

Materials 3 foam cups, a thermometer, 100 mL of 1.0*M* HCl, and approximately 200 mL of 1.0*M* NaOH

Safety Students should wear safety glasses and aprons. HCl and NaOH are corrosive. Caution students to avoid skin contact with these chemicals. Neutralized solutions can be flushed down the drain with excess water.

Procedure Write the balanced chemical equation on the board for students to use as a reference: $HCl(aq) + NaOH(aq) \rightarrow H_2O(l) + NaCl(aq)$ + heat. Have students interpret the balanced equation as 1 mole of HCl reacts with 1 mole of NaOH to form 1 mole of NaCl and 1 mole of water. Have students transfer 30 mL of the HCl to a styrofoam cup and measure the temperature. Next, have them add 10 mL of NaOH and gently stir the contents with the thermometer. Students should record the highest temperature reached as the reaction proceeds. Using a new cup each time, repeat the measurement with 30 mL of HCl and 30 mL of NaOH, and with 30 mL of HCl and 60 mL of NaOH.

Expected Outcomes The second trial, in which reactants are present in a 1:1 mole ratio, produces the greatest temperature change. A slightly lower temperature change for the third trial can be accounted for by the greater mass of reagents. Ask, **Which trial had the highest yield?** *(the one that produced the greatest temperature change)*

Answers to...

Figure 12.13 H_2O and CO_2

Reactions do not always go to completion; side reactions may occur; poor laboratory technique.

Discuss L2

Point out the importance of the yield in a chemical reaction. Note that actual yields are usually less than theoretical yields. For industrial chemists or chemical engineers, the goal is to find cost-effective methods for converting reactants into products. Industrial chemists and chemical engineers want to achieve the maximum product yield at the lowest cost. One way to control costs is to minimize the amount of excess reagent by calculating stoichiometric quantities of the reactants.

Sample Problem 12.9

Answers

29. 59.3 g Fe
30. 17.0 g Ag

Practice Problems Plus L2

Chapter 12 Assessment problem 49 is related to Sample Problem 12.9.

Math Handbook

For a math refresher and practice, direct students to dimensional analysis, page R66.

Sample Problem 12.10

Answers

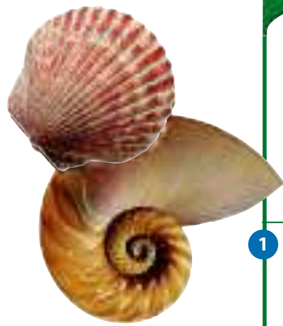
31. 83.5%
32. 57.7%

Practice Problems Plus L2

If 75.0 g of siderite ore ($FeCO_3$) is heated with an excess of oxygen, 45.0 g of ferric oxide (Fe_2O_3) is produced.

$$4FeCO_3(s) + O_2(g) \rightarrow 2Fe_2O_3(s) + 4CO_2(g)$$

What is the percent yield of this reaction? *(87.0%)*



SAMPLE PROBLEM 12.9

Calculating the Theoretical Yield of a Reaction

Calcium carbonate, which is found in seashells, is decomposed by heating. The balanced equation for this reaction is:

$$CaCO_3(s) \xrightarrow{\Delta} CaO(s) + CO_2(g)$$

What is the theoretical yield of CaO if 24.8 g $CaCO_3$ is heated?

1 Analyze *List the knowns and the unknown.*

Knowns
- mass of calcium carbonate = 24.8 g $CaCO_3$
- 1 mol $CaCO_3$ = 100.1 g $CaCO_3$ (molar mass)
- 1 mol CaO = 56.1 g CaO (molar mass)

Unknown
- theoretical yield of calcium oxide = ? g CaO

Calculate the theoretical yield using the mass of the reactant:

$$\text{g } CaCO_3 \longrightarrow \text{mol } CaCO_3 \longrightarrow \text{mol CaO} \longrightarrow \text{g CaO}$$

The appropriate mole ratio is 1 mol CaO/1 mol $CaCO_3$.

2 Calculate *Solve for the unknown.*

$$24.8\ \text{g}\ \cancel{CaCO_3} \times \frac{1\ \cancel{\text{mol}\ CaCO_3}}{100.1\ \text{g}\ \cancel{CaCO_3}} \times \frac{1\ \cancel{\text{mol CaO}}}{1\ \cancel{\text{mol}\ CaCO_3}} \times \frac{56.1\ \text{g CaO}}{1\ \cancel{\text{mol CaO}}}$$

$$= 13.9\ \text{g CaO}$$

3 Evaluate *Does the result make sense?*

The mole ratio of CaO to $CaCO_3$ is 1:1. The ratio of their masses in the reaction should be the same as the ratio of their molar masses, which is slightly greater than 1:2. The result of the calculations shows that the mass of CaO is slightly greater than half the mass of $CaCO_3$.

Math Handbook

For help with dimensional analysis, go to page R66.

Practice Problems

29. When 84.8 g of iron(III) oxide reacts with an excess of carbon monoxide, iron is produced.

$$Fe_2O_3(s) + 3CO(g) \longrightarrow 2Fe(s) + 3CO_2(g)$$

What is the theoretical yield of iron?

30. When 5.00 g of copper reacts with excess silver nitrate, silver metal and copper(II) nitrate are produced. What is the theoretical yield of silver in this reaction?

Interactive Textbook

Problem-Solving 12.29 Solve Problem 29 with the help of an interactive guided tutorial.

with ChemASAP

Recall that the percent yield is calculated by multiplying the ratio of the actual yield to theoretical yield by 100%. Therefore, you must have values of both the theoretical yield and the actual yield to calculate the percent yield.

SAMPLE PROBLEM 12.10

Calculating the Percent Yield of a Reaction

What is the percent yield if 13.1 g CaO is actually produced when 24.8 g $CaCO_3$ is heated?

$$CaCO_3(s) \xrightarrow{\Delta} CaO(s) + CO_2(g)$$

1 Analyze ***List the knowns and the unknown.***

Knowns

- actual yield = 13.1 g CaO
- theoretical yield = 13.9 g CaO (from Sample Problem 12.9)
- $\text{percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

Unknown

- percent yield = ? %

2 Calculate ***Solve for the unknown.***

$$\text{percent yield} = \frac{13.1\ \text{g}\ \cancel{\text{CaO}}}{13.9\ \text{g}\ \cancel{\text{CaO}}} \times 100\% = 94.2\%$$

3 Evaluate ***Does the result make sense?***

In this example, the actual yield is slightly less than theoretical yield. Therefore, the percent yield should be slightly less than 100%. The answer should have three significant figures.

Practice Problems

31. If 50.0 g of silicon dioxide is heated with an excess of carbon, 27.9 g of silicon carbide is produced.

$$SiO_2(s) + 3C(s) \longrightarrow SiC(s) + 2CO(g)$$

What is the percent yield of this reaction?

32. If 15.0 g of nitrogen reacts with 15.0 g of hydrogen, 10.5 g of ammonia is produced. What is the percent yield of this reaction?

Math Handbook

For help with percents, go to page R72.

Interactive Textbook

Problem-Solving 12.31 Solve Problem 31 with the help of an interactive guided tutorial.

with ChemASAP

12.3 Section Assessment

33. **Key Concept** In a chemical reaction, how does an insufficient quantity of a reactant affect the amount of product formed?

34. **Key Concept** How can you gauge the efficiency of a reaction carried out in the laboratory?

35. What is the percent yield if 4.65 g of copper is produced when 1.87 g of aluminum reacts with an excess of copper(II) sulfate?

$$2Al(s) + 3CuSO_4(aq) \longrightarrow Al_2(SO_4)_3(aq) + 3Cu(s)$$

Elements Handbook

Haber Process Read about ammonia on page R26. Examine the flow chart summarizing the Haber process. What experimental data would you need to determine the percent yield of the Haber process?

Interactive Textbook

Assessment 12.3 Test yourself on the concepts in Section 12.3.

with ChemASAP

3 ASSESS

Evaluate Understanding L2

Limiting Reaction

Following the safety precaution listed in the Quick Lab on page 372, place a small piece of zinc in a large beaker of dilute hydrochloric acid. Explain the reaction to the students.

$$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$$

Ask, **Which of the two reactants is the limiting reagent?** *(If the zinc completely disappears after some time, students may conclude that the zinc is used up first, and is, therefore, the limiting reagent.)* After students respond, ask, **How can you test your hypothesis?** (*Acceptable answers include measure the volume of H_2 produced for various amounts of zinc added to a fixed volume of HCl. Determine the stoichiometric quantity of zinc, the amount that reacts to give the greatest volume of H_2.*)

Reteach L1

Emphasize the importance of having a correctly balanced equation in order to properly calculate the theoretical yield for a reaction. Explain that the way to decide which substance, if any, is the limiting reagent, is to compare the mole ratios of the given substances to the required mole ratio, as shown in the balanced chemical equation.

Elements Handbook

the amounts of N_2 and H_2 used (to calculate the theoretical yield), and the amount of NH_3 produced (i.e., the actual yield)

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 12.3.

with ChemASAP

Section 12.3 Assessment

33. In a chemical reaction, an insufficient quantity of any of the reactants will limit the amount of product that forms.

34. The efficiency of a reaction carried out in a laboratory can be measured by calculating the percent yield.

35. 70.5%

Technology & Society

Just the Right Volume of Gas

Write the following reactions on the board.

Reaction I $2NaN_3(s) \rightarrow 2Na(s) + 3N_2(g)$
Reaction II $10Na(s) + 2KNO_3(s) \rightarrow K_2O(s) + 5Na_2O(s) + N_2(g) + \text{heat}$

Point out that the proper inflation of the air bag requires two reactions. Explain that an electrical current produced by the igniter causes the decomposition of sodium azide into sodium metal and nitrogen gas. Note that the sodium metal produced is dangerously reactive. In a second reaction, potassium nitrate reacts with the elemental sodium and forms potassium oxide, sodium oxide, and additional nitrogen gas. The heat causes all the solid products to fuse with SiO_2, powdered sand, which is also part of the reaction mixture. The fused product is a safe, unreactive glass.

Discuss L2

Ask, **How many moles of potassium nitrate must be included in the reaction mixture to consume the sodium produced by the decomposition of one mole of sodium azide?** *(0.2 mol KNO_3)* **How many liters of N_2 are produced at STP if 1.0 mole of sodium azide and 0.20 mole of potassium nitrate react?** *(36 L)* Have students speculate how the pressure of the gas inside the air bag depends on the number of moles of nitrogen produced and the temperature inside the air bag. *(Acceptable answers should indicate that because gas pressure depends on the number of gas particles present, pressure depends on the number of moles of gas particles present. The heat released by this reaction raises the temperature of the gaseous products, helping the bag inflate even faster.)*

Technology & Society

Just the Right Volume of Gas

In a front-end collision, proper inflation of an air bag may save your life. Engineers use stoichiometry to determine the exact quantity of each reactant in the air bag's inflation system. **Interpreting Diagrams** ***What is the source of the gas that fills an air bag?***

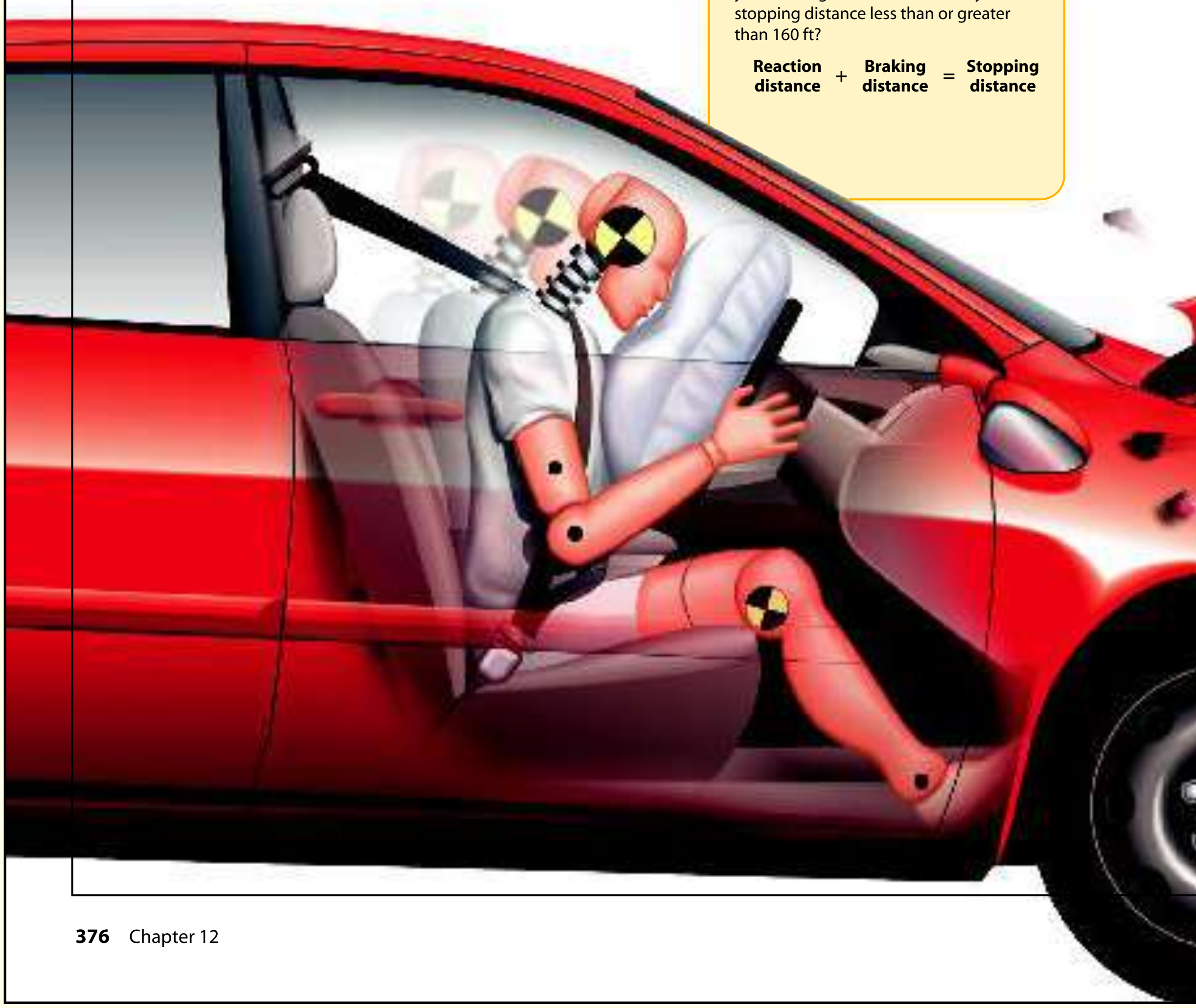
Car Facts

17.1 million cars and light trucks were sold in 2002 in the United States.

Monaco has the highest number of vehicles in relation to its road network. In 1996 (most recent figures), it had 480 vehicles for each kilometer of road. If they were required to park behind one another on the streets, half would have nowhere to park!

At night, headlights illuminate 160 ft in front of your car. If you are driving 40 mi/h at night, your reaction distance is 88 ft and your braking distance is 101 ft. Is your stopping distance less than or greater than 160 ft?

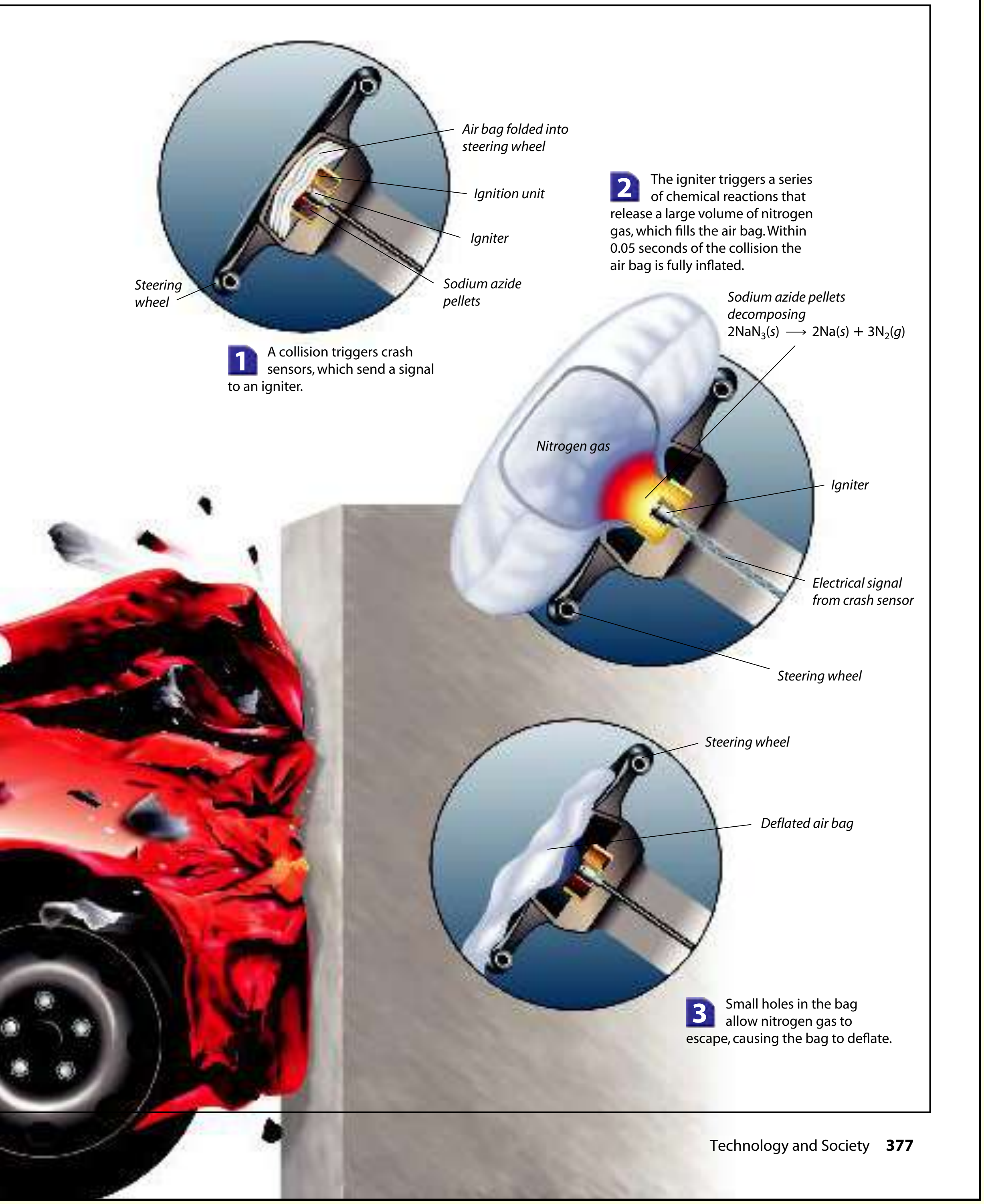
Reaction distance + **Braking distance** = **Stopping distance**



Facts and Figures

Automobile Restraint Systems

History	
1947	Tucker Automobile Company makes safety belts available.
1949	Nash Motor Company provides lap-safety belts.
1958	Swedish engineer, Nils Bohlin, patents chest/lap-safety belt.
1963	Volvo makes chest/lap-safety belts standard equipment on its U.S. models.
1988	Chrysler Motor Company makes air-bag restraint systems standard equipment.



Facts and Figures

Automobile Restraint Systems

Statistic The use of air-bag restraint systems (seatbelt/air bags) reduces the risk of fatalities in accidents by about 70%.

Discuss L2

Have students research the safety restrictions on the use of air bags with infants and young children. Have students research new designs and applications of safety air bags.

Answers to...

Interpreting Diagrams

The sources of the N_2 gas are the decomposition reaction of sodium azide (NaN_3) and the reaction of sodium with potassium nitrate.