5.1 Synthesis and Decomposition Reactions

Key Terms
precipitate
synthesis reaction
decomposition reaction

In 1988, while flying at an altitude of over 7 km, an airplane lost a large portion of its upper fuselage, shown in **Figure 5.1**. Investigators determined that a major contributing factor to this incident was metal corrosion.

In previous science studies, you may have learned that using road salt in winter has an unwanted side effect of promoting the corrosion of vehicles and other human-made structures. This particular type of corrosion involves the formation of rust. Scientifically, the chemical name for rust is iron(III) oxide, and the chemical formula is Fe_2O_3. Iron(III) oxide is produced, or synthesized, from the reaction between iron and oxygen. The balanced chemical equation for the formation of iron(III) oxide is

$$4Fe(s) + 3O_2(g) \rightarrow 2Fe_2O_3(s)$$

Both iron and steel (an alloy of iron, carbon, and other elements) are important components of numerous products that are damaged by rust. Therefore, understanding this reaction and developing ways to prevent rust and corrosion are important areas of scientific study.

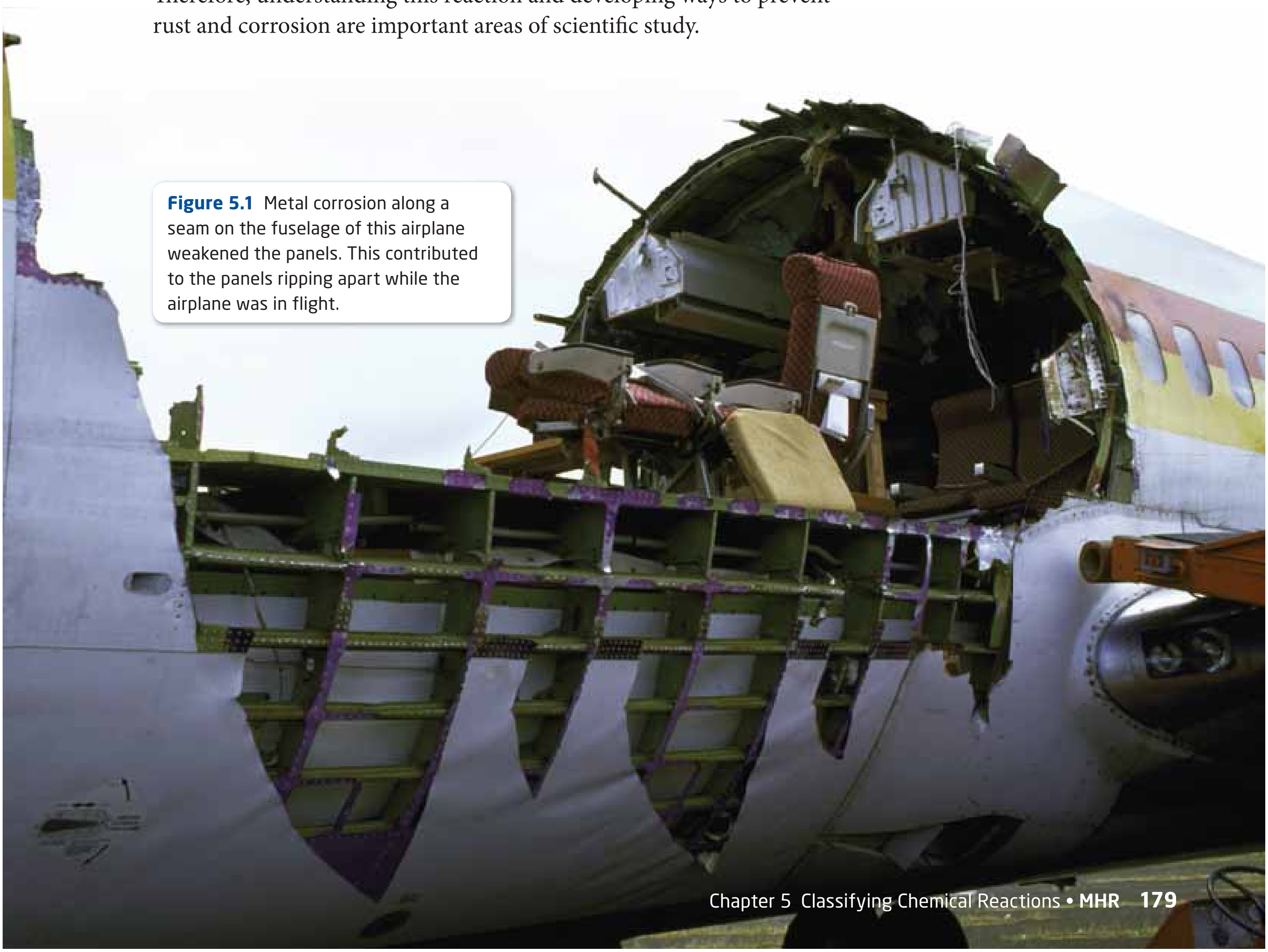


Figure 5.1 Metal corrosion along a seam on the fuselage of this airplane weakened the panels. This contributed to the panels ripping apart while the airplane was in flight.

Evidence of Chemical Change

precipitate an insoluble solid formed in a chemical reaction

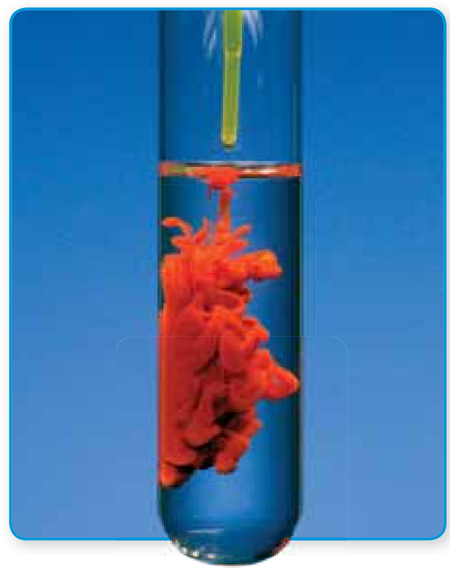
Studying chemical reactions involves looking closely at chemical changes. You are already familiar with a number of chemical changes. When wood in a campfire burns, a chemical change occurs. Photosynthesis, in which plants change water and carbon dioxide into glucose and oxygen, is also a chemical change. New substances are made in each of these processes. It is not always easy to tell if a new substance forms during a change. There are some clues, however, that you can use to tell if a chemical change has occurred. For example, a reaction might create a new product that is an insoluble solid, called a **precipitate**. This precipitate is a new substance and, therefore, is evidence that a chemical change has occurred. As shown in **Figure 5.2**, six clues that suggest a chemical change is occurring are formation of a gas, formation of a precipitate, change in colour, change in odour, change in temperature, and production of light.

Suggested Investigation

Plan Your Own Investigation 5-A, Evidence of Chemical Change, on page 207

The formation of a gas

The formation of a precipitate and a change in colour



A change in odour

The production of light and heat

Figure 5.2 Several pieces of evidence can point to the possibility of a chemical change. For example, a new product that is a gas or precipitate may form. Also, a change in colour, odour, or temperature, or light being emitted can indicate that a new substance has formed.

Classifying Chemical Reactions

The new substances, or products, that form during chemical changes will depend on the type of chemical reaction occurring. Understanding the different types of chemical reactions will allow you to identify what products are most likely to form. Chemists classify chemical reactions into different categories. In this chapter, you will study four different types of reactions: synthesis, decomposition, single displacement, and double displacement. The name of each reaction provides a clue about how the reactants change into products.

As you learn about each of the four types of reactions presented in this chapter, be sure to note the reactants and the products formed. You might want to record what you learn using a graphic organizer. This will help you to recognize the reaction types and to make predictions about the products.

synthesis reaction a chemical reaction in which two or more reactants combine to produce a new product

Synthesis Reactions

A **synthesis reaction** is a chemical reaction in which two or more reactants combine to form a new product. Synthesis reactions can be represented by a general chemical equation and pictorially as

$$A + B \rightarrow AB$$

This means that two or more reactants (A and B) combine to form one product (AB). The reactants may be any combination of elements and compounds, but the product will always be a compound.

Figure 5.3 shows a space shuttle blasting off. The incredible power of its main thruster is generated from a synthesis reaction. The reactants are liquid hydrogen and liquid oxygen, which combine to form water vapour. The balanced chemical equation for this reaction is

$$2H_2(\ell) + O_2(\ell) \rightarrow 2H_2O(g)$$

Recall that both oxygen and hydrogen exist as diatomic molecules. As discussed in Chapter 4, the other five that you should know are nitrogen (N_2), fluorine (F_2), bromine (Br_2), iodine (I_2), and chlorine (Cl_2). It is important to keep in mind that these elements exist as diatomic molecules, and that all of them except bromine and iodine are gases at room temperature. At room temperature, bromine is a liquid and iodine is a solid. This knowledge will be important when indicating states of reactants and products in chemical equations.

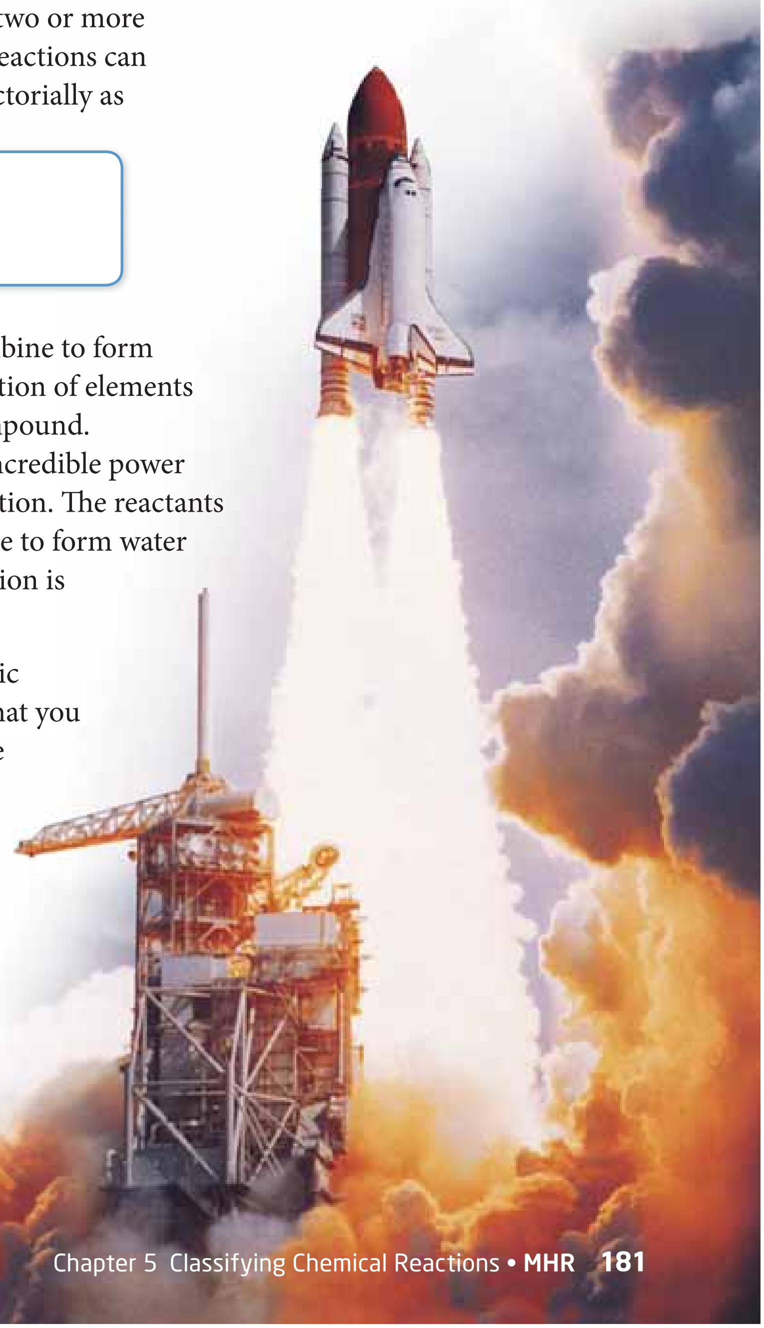


Figure 5.3 The synthesis reaction between hydrogen and oxygen helps to propel a space shuttle into orbit.

The Haber Process

One important product made by a synthesis reaction is ammonia, $NH_3(g)$. Ammonia is an important component in fertilizers. Nitrogen is essential to all living things. To optimize crop yields, farmers often supply nitrogen to their fields by applying fertilizers, as shown in **Figure 5.4**.

Ammonia also serves important roles in making paper, in extracting zinc and nickel from ores, in explosives, and in cleaning products.

Ammonia is the product of the synthesis reaction between the elements nitrogen and hydrogen. Fritz Haber, a German chemist, patented a process for performing this reaction in 1910. Chemists often refer to this reaction as the Haber process. The reaction is carried out under high temperature and pressure. The balanced chemical equation for this reaction is

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

Figure 5.4 The synthesis of ammonia is an important industrial reaction. For example, ammonia and many compounds formed from it provide nitrogen in a form that plants can absorb.

STSE Case Study

Hydrogen: Fuel of the Future?

In North America, most of our transportation and industries rely on fossil fuels. Cars, trains, and airplanes run on petroleum products. Many power plants use oil, natural gas, and coal. A significant problem with this fossil fuel economy is that these fossil fuels, which took millions of years to form, are being depleted.

Hydrogen as a Fuel

Ballard Power Systems' response to this problem was to develop the first hydrogen fuel cell-powered transit bus for trial in Vancouver in 1993. BC Transit plans to continue its commitment to creating a zero-emissions transit system by showcasing the world's first demonstration fleet of hydrogen fuel cell buses at the 2010 Winter Olympics in Whistler.

Hydrogen is a plentiful element, and it is much cleaner to use than fossil fuels because it produces no greenhouse gas emissions. Hydrogen fuel cells produce electrical energy directly from the reaction between hydrogen and oxygen. Heat and water are the only by-products of fuel cells that use hydrogen.

However, hydrogen is usually bonded with other elements in compounds, such as water or natural gas. It takes energy to produce the chemical reactions that yield hydrogen from such compounds.

Because a hydrogen fuel cell produces no emissions, it is an environmentally friendly energy source.

Synthesis of Atmospheric Pollutants

Many atmospheric pollution problems, shown in **Figure 5.5**, are associated with synthesis reactions. For example, as discussed in Chapter 4, nitrogen gas in the atmosphere can react with oxygen to form a class of compounds called nitrogen oxides. These compounds are gases composed of differing proportions of nitrogen and oxygen. Chapter 8 includes a discussion of these greenhouse gases and their contribution to climate change.

A colourless molecular compound called nitrogen monoxide, NO(g), is initially formed in a reaction that is represented by the chemical equation

$$N_2(g) + O_2(g) \rightarrow 2NO(g)$$

The nitrogen monoxide can then undergo another synthesis reaction that produces a brown reactive gas called nitrogen dioxide, $NO_2(g)$. This reaction occurs according to the chemical equation

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$$

Figure 5.5 The synthesis reaction between oxygen and nitrogen produces nitrogen dioxide, which contributes to the hazy appearance of smog.

Toronto's Hydrogen Village

A Hydrogen Village project is being developed in the Greater Toronto Area. This project has several goals. For example, it will strive to create commercial markets for hydrogen and fuel cell applications. It will provide information about the benefits of hydrogen and fuel cells. It will also encourage investment in, and development of, hydrogen and fuel cell technologies.

This hydrogen refuelling station is at Exhibition Place in Toronto.

Challenges Associated with Implementing a Hydrogen Economy

- It takes a large amount of energy to produce and transport hydrogen.
- It is costly to transport and store hydrogen.
- Hydrogen is a bulky gas to store and is highly flammable.
- Hydrogen fuelling stations are not readily available.

Your Turn

1. Based on this case study, list the benefits and challenges of a hydrogen economy. What problems must we solve before hydrogen fuel can be used extensively?
2. "One of the most urgent challenges of our generation is switching from a fossil fuel economy to a hydrogen fuel economy." Do you agree or disagree with this statement? Provide two reasons to support your position.
3. Choose a country that is part of the International Partnership for the Hydrogen Economy. Research what advances that country has made in the use of hydrogen as a fuel. Present your findings to the class.

Synthesizing Binary Ionic Compounds

Although products of chemical reactions are identified and studied experimentally, it is sometimes useful to determine the products that are most likely to form in a reaction. For the synthesis of binary ionic compounds composed of metals with one possible ion charge, you can use ion charges to determine the most likely product.

GRASP
Go to **Science Skills Toolkit 11** to learn about an alternative problem solving method.

Sample Problem: Making Binary Ionic Compounds with Univalent Metals

Problem

Complete and balance the following synthesis reaction.

$$Na(s) + Cl_2(g) \rightarrow$$

Solution

Step 1: This is a synthesis reaction. Therefore, the two reactants combine to form a single product.

Step 2: You can use the ion charges to determine the most likely product. Sodium has an ion charge of 1+, and chlorine has an ion charge of 1−.

Step 3: For the product to have a net charge of zero, it must be composed of a 1:1 ratio of sodium ions and chloride ions. Therefore, the product is NaCl. The cross-over method for determining the chemical formula is shown in the margin.

Cross-Over Method

Na^{+} Cl^{-}

NaCl

Step 4: The problem also asks for a balanced chemical equation for the reaction. First, write the skeleton equation.

$$Na(s) + Cl_2(g) \rightarrow NaCl(s)$$

Then, balance the equation using coefficients.

$$2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$$

Check Your Solution

First, check to make sure that the product consists of a combination of all the elements in the reactants. Then, make sure that the total sum of positive and negative ion charges gives a net charge of zero for the compound. Count the number of each type of atom in the final chemical equation to make sure the equation is balanced.

Figure 5.6 The hydrogen gas (in the tank) is ignited to provide an increase in temperature that is needed for the reaction with chlorine gas (in the flask) to occur.

Practice Problems

1. Complete and balance the following synthesis reactions.
Note: All the products formed in these reactions are solids.

a. $Ca(s) + N_2(g) \rightarrow$

b. $K(s) + O_2(g) \rightarrow$

c. $Cs(s) + P_4(s) \rightarrow$

d. $Al(s) + F_2(g) \rightarrow$

2. Write a balanced chemical equation for the synthesis reaction between hydrogen gas and chlorine gas, shown in **Figure 5.6**. Note that the product is a gas.

Learning Check

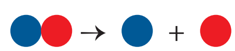
1. What is the general chemical equation for a synthesis reaction?
2. Predict the product that forms in the synthesis reaction between potassium metal and iodine gas. Provide the balanced chemical equation for the reaction. Explain your reasoning.
3. Determine whether each of the following chemical equations is a synthesis reaction.
   a. $2Cr(s) + 3F_2(g) \rightarrow 2CrF_3(s)$
   b. $2Al(s) + 3SnCl_2(aq) \rightarrow 2AlCl_3(aq) + 3Sn(s)$
   c. $2Ti(s) + 3Cl_2(g) \rightarrow 2TiCl_3(s)$
4. Use your understanding of the term *synthesis* to infer the meanings of the terms *synthetic* and *synthesize*.

Decomposition Reactions

A **decomposition reaction** is a chemical reaction in which a compound breaks down into two or more products. Decomposition reactions can be represented by a general chemical equation and pictorially as

decomposition reaction a chemical reaction in which a compound breaks down (decomposes) into two or more simpler compounds or elements

$$AB \rightarrow A + B$$



The products may be any combination of elements and compounds, but the reactant will always be a compound. A decomposition reaction is the reverse of a synthesis reaction.

An essential component in the development of hydrogen as a fuel source is the ability to produce sufficient amounts of hydrogen. One way that hydrogen gas is produced is through the decomposition of water. Electric current is used to break apart the bonds between the hydrogen and oxygen atoms to form the separate elements. The reaction is represented by the chemical equation

$$2H_2O(\ell) \rightarrow 2H_2(g) + O_2(g)$$

This process is referred to as the electrolysis of water. Almost 4 percent of the hydrogen gas used in the world is produced by decomposition of water. A laboratory demonstration of electrolysis is shown in **Figure 5.7**.

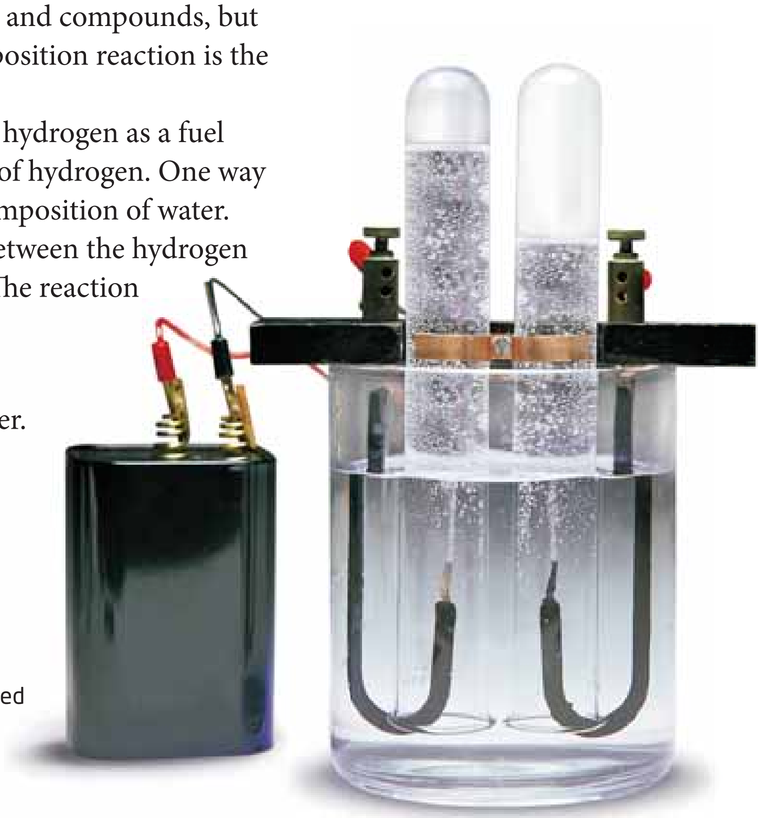


Figure 5.7 The electric current supplied by the battery provides the energy needed to decompose water into the elements hydrogen and oxygen.

Decomposition Reactions and Explosives

Go to **scienceontario** to find out more

The electrolysis of water is an example of a decomposition reaction that results in the production of elements. The tremendous forces associated with the explosion in **Figure 5.8** are the result of a decomposition reaction that produces several substances. Trinitrotoluene (TNT), $C_7H_5N_3O_6(s)$, is a commonly used explosive that decomposes into elements and compounds according to the chemical equation

$$2C_7H_5N_3O_6(s) \rightarrow 3N_2(g) + 5H_2O(g) + 7CO(g) + 7C(s)$$

Three of the products of the decomposition of TNT—nitrogen, water, and carbon monoxide—are gases. The formation and rapid expansion of these gases pushes material away from the blast site, producing the explosion.

Figure 5.8 Explosives, like the ones used in this coal mine blast, produce tremendous force to break apart rocks. They can occur as a result of the decomposition of a compound and the rapid heating and expansion of the gases that are produced.

Products Made in the Decomposition of Ionic Compounds

Just as you saw for synthesis reactions, it is sometimes useful to identify the products that are most likely to form in a decomposition reaction. For the purposes of this course, you will learn to determine the most likely products of decomposition reactions of ionic compounds that form elements. During the decomposition of an ionic compound, electrons transfer back to the atoms of the metal, and each element becomes electrically neutral. Read through the sample problem on the next page. Then practise writing the products in the decomposition of ionic compounds by completing the practice problems.

Sample Problem: Elements Formed from the Decomposition of Ionic Compounds

Problem

Complete and balance the following decomposition reaction.

$$AgCl(s) \rightarrow$$

Solution

Step 1: This is a decomposition reaction. Therefore, the reactant decomposes into the two elements that it is composed of—silver and chlorine.

Step 2: Silver is a metal and is represented as Ag(s). Chlorine is one example of a diatomic molecule, and it exists as a gas. Therefore, it must be represented as $Cl_2(g)$.

Step 3: The problem also asks for a balanced chemical equation for the reaction. First, write the skeleton equation.

$$AgCl(s) \rightarrow Ag(s) + Cl_2(g)$$

Then balance the equation using coefficients.

$$2AgCl(s) \rightarrow 2Ag(s) + Cl_2(g)$$

Check Your Solution

First, check to make sure that the product consists of the two elements present in the reactant. Then, if any of the products are diatomic molecules, ensure that they are represented correctly. Count the number of each type of atom in the final chemical equation to make sure that the equation is balanced.

Study Toolkit

Identifying Cause and Effect Examine the sample problem. Identify signal words and phrases that indicate a cause-and-effect relationship. Describe the relationship(s) you have identified.

GRASP

Go to **Science Skills Toolkit 11** to learn about an alternative problem solving method.

Practice Problems

1. Complete and balance the following decomposition reactions. **Note:** All metal products are solids, and any remaining products are gases.

a. $AuCl_3(s) \rightarrow$

b. $MgF_2(s) \rightarrow$

c. $Li_2O(s) \rightarrow$

d. $CsCl(s) \rightarrow$

2. Write the chemical equation for the decomposition of chromium(III) oxide into solid chromium and oxygen gas.

3. Many automobile airbags rely on decomposition of the compound sodium azide, NaN_3, to produce nitrogen gas that rapidly inflates the bag, shown in **Figure 5.9**. Sodium metal is also produced in the reaction. Write the balanced chemical equation for this decomposition reaction.

Figure 5.9 Airbag technology has relied on the decomposition of sodium azide. The reaction is triggered by an electrical impulse, and nitrogen gas is produced, which inflates the bag.

Activity 5-2

Building Up and Breaking Down

In this activity, you will practise several ways to represent a chemical reaction while analyzing the reactants and products of synthesis and decomposition reactions. How can models help you remember what is occurring in each type of reaction?

Materials

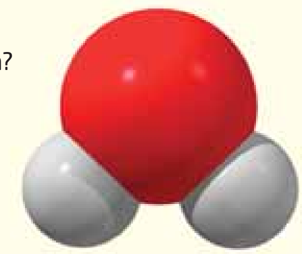
- molecular modelling kit

Procedure

1. Make a table with the following headings: Word Equation, Skeleton Equation, Model Equation, and Balanced Chemical Equation. Give your table a title.
2. Examine the reactions described below. Write a word equation and a skeleton equation for each reaction in your table.
   a. Hydrogen and oxygen react to form water, accompanied by the release of heat.
   b. When heated, calcium carbonate decomposes to form carbon dioxide and calcium oxide.
   c. Carbon and oxygen react to form carbon dioxide, producing heat.
3. In a group, use the molecular modelling kit to make a model of each substance. Once your models are made, arrange them into a skeleton equation for each reaction.
4. Balance each chemical equation by adding or removing whole models until the total number of each atom is the same in the reactants and products. In your table, draw a diagram to show the models you used.
5. Based on your work with the models, add coefficients to each skeleton equation to write balanced chemical equations in your table.

Questions

1. Which chemical equations represent a decomposition reaction? Explain your reasoning.
2. Which chemical equations represent a synthesis reaction? Explain your reasoning.
3. How has using models helped you understand what is occurring in each reaction?



Water contains hydrogen and oxygen.

Suggested Investigation

Inquiry Investigation 5-B, Synthesis and Decomposition Reactions, on page 208

Figure 5.10 This worker is standing inside a kiln that is used for heating calcium carbonate. Kilns are ovens used for heating or drying materials.

Synthesis and Decomposition in Construction

The next time you go out, look around and notice the many things that are made using concrete. A component of concrete is the ionic compound calcium oxide, CaO. Calcium oxide is made by decomposing another ionic compound, calcium carbonate, $CaCO_3$. The calcium carbonate is mined in the form of limestone. When calcium carbonate is heated in a kiln, shown in **Figure 5.10**, it decomposes into calcium oxide and carbon dioxide. The balanced chemical equation for the decomposition of calcium carbonate is

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

When needed to make mortar or plaster, the calcium oxide is combined with water in the synthesis reaction

$$CaO(s) + H_2O(\ell) \rightarrow Ca(OH)_2(aq)$$

The resulting mortar is watertight and has enough flexibility to help prevent cracks.

Section 5.1 Review

Section Summary

- Evidence of a chemical change may include one or more of the following: formation of a gas, formation of a precipitate, change in odour, change in colour, change in temperature, and production of light.
- During a synthesis reaction, two or more reactants combine to form one product. The general chemical equation for a synthesis reaction is $A + B \rightarrow AB$. The reactants may be any combination of elements and compounds, but the product will always be a compound.
- During a decomposition reaction, a single reactant breaks down to form two or more products. The general chemical equation for a decomposition reaction is $AB \rightarrow A + B$. The products may be any combination of elements and compounds, but the reactant will always be a compound.
- Examples of synthesis reactions include the formation of rust and production of ammonia. Important decomposition reactions include the electrolysis of water and the explosion of TNT.

Review Questions

K/U **1.** Describe what happens during a synthesis reaction.

K/U **2.** Provide an example of a synthesis reaction that has important industrial applications.

T/I **3.** Describe the chemical reaction that is associated with the corrosion of the structure shown on the right. Write a balanced chemical equation for the reaction.

K/U **4.** Describe what happens during a decomposition reaction.

A **5.** Describe why the process shown in **Figure 5.7** on page 185 is considered a decomposition reaction. Write a balanced chemical equation for the reaction.

C **6.** Use a drawing to demonstrate why synthesis reactions are considered the reverse of decomposition reactions.

K/U **7.** Balance the following chemical equations, and identify each reaction as a synthesis reaction or a decomposition reaction. Provide an explanation for your choice.

a. $Ca(s) + O_2(g) \rightarrow CaO(s)$

b. $Ca(s) + S_8(s) \rightarrow CaS(s)$

c. $CsCl(s) \rightarrow Cs(s) + Cl_2(g)$

K/U **8.** Based on the reactants, determine the products that are most likely to form in the following reactions. Explain your reasoning. You do not need to indicate the states of the products.

a. $Mg(s) + N_2(g) \rightarrow$

b. $K_2O(s) \rightarrow$

c. $Na(s) + Br_2(\ell) \rightarrow$