4.3 Conservation of Mass and Chemical Equations

Key Terms
reactant
product
chemical reaction
chemical equation
coefficient

In July 1992, there was a tragic fire in the Chemistry Department at the University of Western Ontario. The fire claimed the life of a student who was working in a chemistry lab. The cause of the accident was linked to the reaction between water and sodium metal. Water had contaminated a sample of alcohol, and sodium is very reactive with water, as shown in **Figure 4.18**. The reaction generated flammable hydrogen gas that ignited and caused an explosion.

During the clean-up of this accident, a second student was injured. Small pieces of sodium that had not completely reacted had been scattered by the explosion. A lab assistant apparently touched a piece of sodium with a wet paper towel, causing another reaction. This reaction occurred near a container of liquid waste that was giving off flammable vapours. The vapours ignited, and a second fire started. Accidents like these emphasize the importance of following safety procedures and having a thorough understanding of how chemicals react.

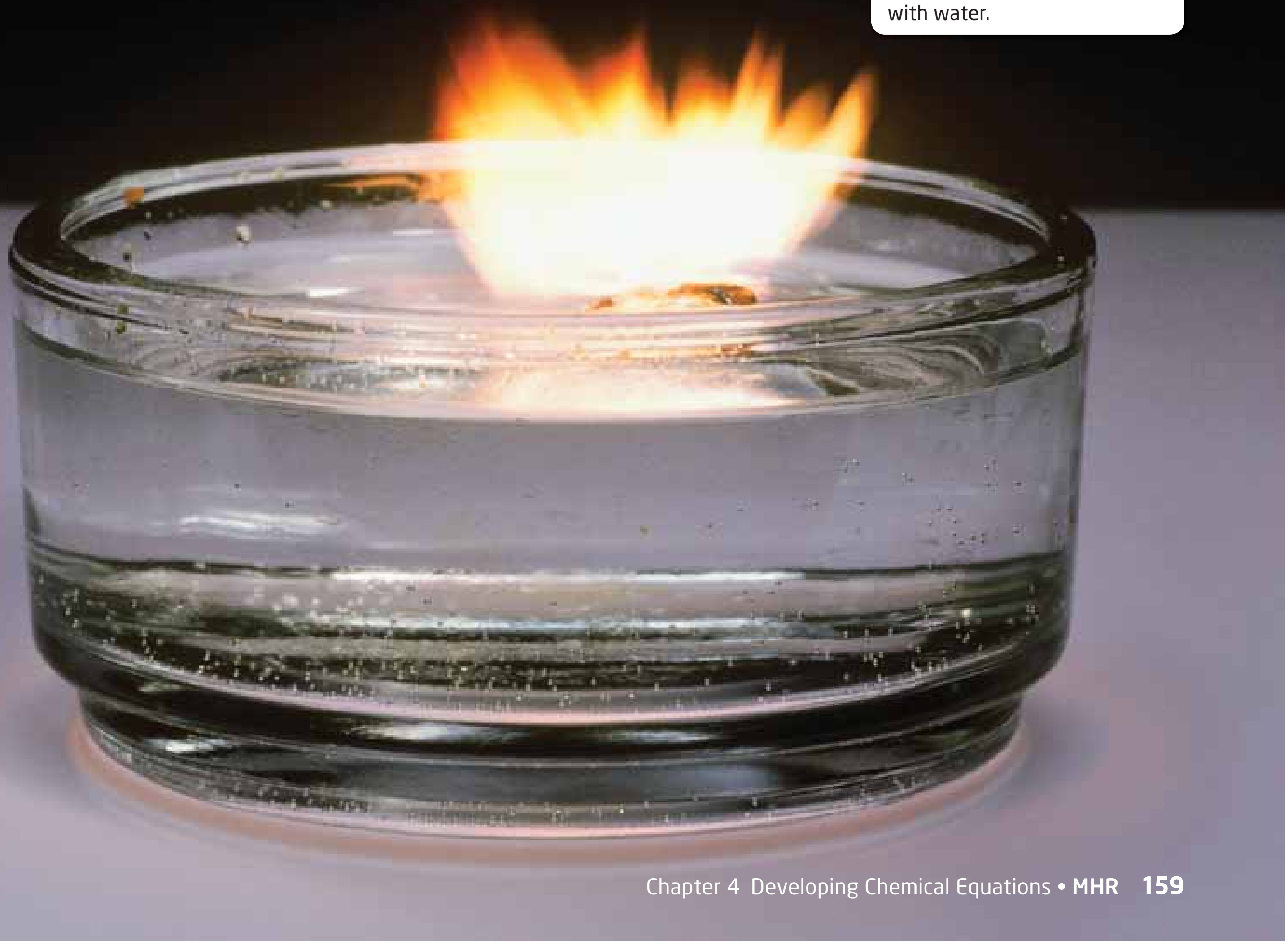


Figure 4.18 To avoid lab accidents, people who work with chemicals must follow safety precautions and understand how chemicals can react. This is especially important when handling potentially dangerous materials like this sodium metal, which is highly reactive with water.

Conservation of Mass in Chemical Changes

reactant a pure substance that undergoes a chemical change

product a pure substance that is formed in a chemical change; the properties of the product are different from the properties of the reactants

chemical reaction a process in which new substances with new properties are formed

You have learned that a chemical change involves the reaction of a substance to produce a new substance. A chemical change always involves the conversion of substances, called **reactants**, into other substances, called **products**. For example, in the reaction shown in the opener on the previous page, sodium and water are the reactants and hydrogen is one of the products. The properties of the products are different from the properties of the reactants, even though the products have the same atoms as the reactants. In a chemical reaction, atoms are conserved (they are neither created nor destroyed). The atoms, however, are rearranged to form new substances. A **chemical reaction** is one or more chemical changes that occur at the same time.

In the late 1700s, a French chemist named Antoine Lavoisier, shown in **Figure 4.19**, greatly advanced the study of chemistry. Lavoisier was very good at examining the work of other scientists and then performing his own experiments and composing an explanation of what he observed. One of his strengths as a researcher was his careful measurement of mass. He performed many experiments in which he carefully measured the mass of the reactants, performed a reaction in a closed container, and carefully measured the mass of the products. For example, he worked with mercury(II) oxide, which forms mercury and oxygen when heated. Time after time, his results were the same: the total mass of the reactants equalled the total mass of the products. He summarized his results in the *law of conservation of mass*.

Suggested Investigation

Inquiry Investigation 4-C, Comparing the Masses of Reactants and Products, on page 172

Law of Conservation of Mass

In a chemical reaction, the total mass of the products is always the same as the total mass of the reactants.

Go to **scienceontario** to find out more

Lavoisier's work allowed John Dalton to re-introduce the idea of atoms to the world in the early 1800s. Since atoms make up each reactant and product, Dalton suggested that each atom in the reactants is also present in the products.

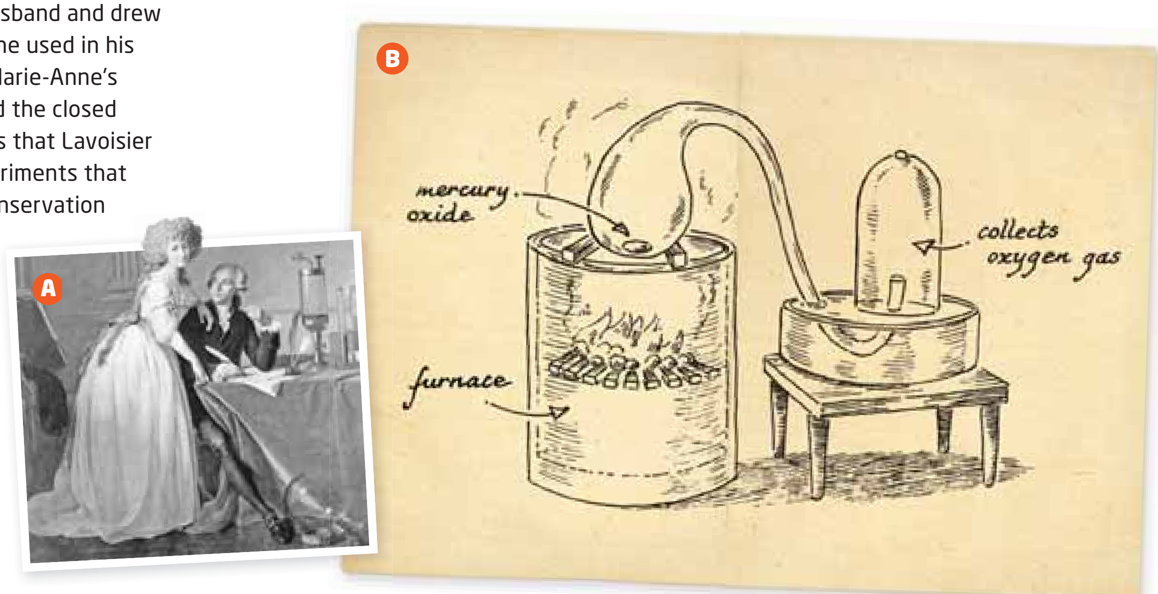


Figure 4.19 **A** Antoine and Marie-Anne Lavoisier were a successful scientific team. Marie-Anne translated scientific papers published in English into French for her husband and drew the instruments he used in his experiments. **B** Marie-Anne's sketches included the closed system apparatus that Lavoisier used for his experiments that demonstrated conservation of mass.

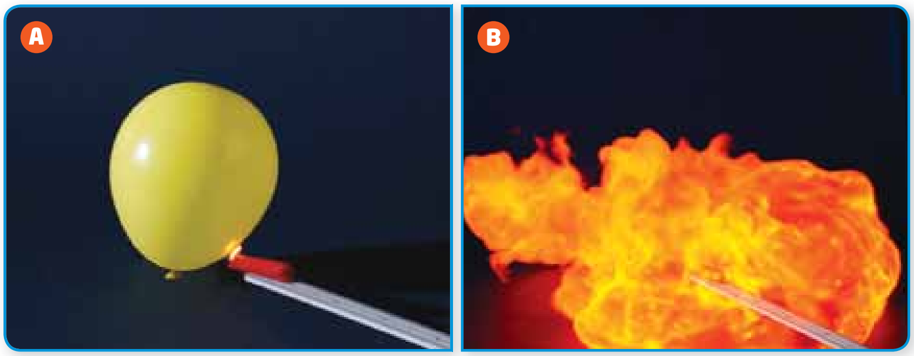


Figure 4.20 **A** A flame is used to ignite a mixture of hydrogen and oxygen. **B** Water forms, with a loud explosion.

Writing Chemical Equations

A **chemical equation** is used to represent a chemical reaction. For example, **Figure 4.20** shows the reaction between oxygen and hydrogen in a balloon to produce water. There are three forms of chemical equations that we can use to represent this: a word equation, a skeleton equation, and a balanced chemical equation.

chemical equation
a representation of what happens to the reactants and products during a chemical change

Word Equations In a *word equation*, the name of each reactant is written to the left of an arrow and the name of each product to the right of the arrow. A plus sign on the reactant side means *reacts with*. A plus sign on the product side means *and*. The arrow stands for *yields* or *reacts to produce*. The word equation for the reaction between hydrogen and oxygen is

$$\text{hydrogen} + \text{oxygen} \rightarrow \text{water}$$

Skeleton Equations A word equation shows the reactants and products of a reaction, but it does not provide information about the chemical composition of the substances. Replacing the words with chemical formulas produces a skeleton equation. The *skeleton equation* for the reaction between hydrogen and oxygen is

$$H_2 + O_2 \rightarrow H_2O$$

Balanced Chemical Equations Although the skeleton equation shows the composition of each substance in the reaction, it does not show the units of reactants that react and units of products produced. A *balanced chemical equation* demonstrates the law of conservation of mass, which requires the same number of atoms of each element to appear on both sides of a chemical equation. A **coefficient** is a number that is placed in front of a chemical formula in a balanced equation to show how many units of the substance are involved in the reaction. The balanced chemical equation for the reaction of hydrogen with oxygen is

coefficient
a number that is placed in front of a chemical formula in a balanced chemical equation

$$2H_2 + O_2 \rightarrow 2H_2O$$

It is very important to remember that the only way to balance a chemical equation is to add coefficients. If you change a subscript, you will change the identity of the substance. For example, if you had tried to balance the skeleton equation above by adding 2 as a subscript to the oxygen in the chemical formula for water, the formula would become H_2O_2, which is the chemical formula for hydrogen peroxide.

Showing the State of a Substance

To complete a balanced chemical equation, the states of the reactants and products at the temperature of the reaction may be included. **Table 4.12** shows the abbreviations used to identify the states of substances in chemical equations. These are placed at the ends of the chemical formulas.

Study Toolkit

Identifying the Main idea and Details Examine the material on this page. Draw a spider map like the one on page 138 to show the main idea and supporting details of the text. Organizing the material in this way will help you to understand the important concepts.

Table 4.12 Abbreviations for the States of Reactants and Products

State	Abbreviation	Example (at room temperature)
Solid	(s)	sodium chloride: NaCl(s)
Liquid	(ℓ)	water: $H_2O(\ell)$
Gas	(g)	hydrogen: $H_2(g)$
Aqueous solution	(aq)	aqueous sodium chloride solution: NaCl(aq)

Reactions in a Rebreather

To take amazing photographs and videos, underwater photographers often need to use a rebreather, as shown in **Figure 4.21**. A rebreather allows a photographer to rebreathe the air that has been exhaled, with some oxygen added in. One kind of rebreather prevents any exhaled gas from escaping, which prevents bubbles that might scare wildlife. The rebreather contains chemicals that react with the exhaled carbon dioxide and remove it from the recirculated air. The chemical reactions that are involved in a rebreather are shown below. Including the states of the reactants and products provides important information.

First, the carbon dioxide gas combines with liquid water to form an aqueous solution of carbonic acid, H_2CO_3.

$$CO_2(g) + H_2O(\ell) \rightarrow H_2CO_3(aq)$$

Next, the carbonic acid solution reacts with an aqueous solution of sodium hydroxide.

$$H_2CO_3(aq) + 2NaOH(aq) \rightarrow Na_2CO_3(aq) + 2H_2O(\ell)$$

Finally, the sodium carbonate reacts with calcium hydroxide, which results in the original atoms from carbon dioxide gas becoming part of solid calcium carbonate.

$$Ca(OH)_2(aq) + Na_2CO_3(aq) \rightarrow CaCO_3(s) + 2NaOH(aq)$$

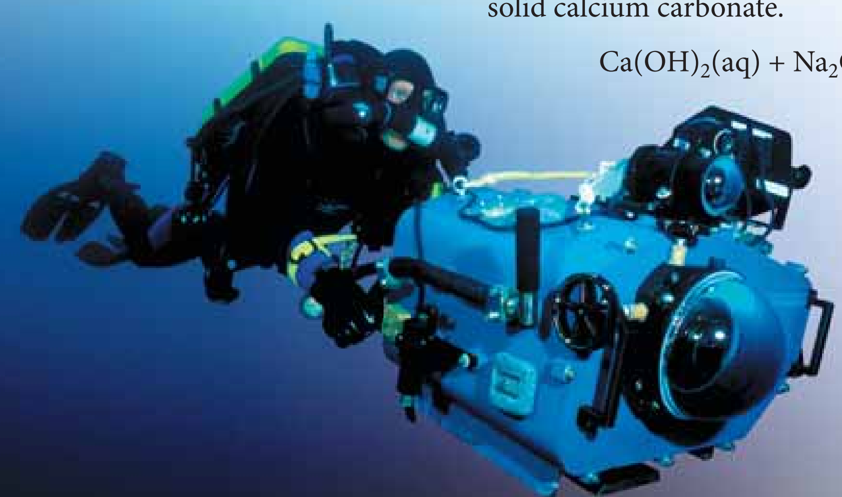


Figure 4.21 This photographer is using a rebreather, which prevents bubbles that might ruin a terrific picture.

Balancing Chemical Equations

The steps below summarize how to use coefficients to balance chemical equations. The formation of water from hydrogen and oxygen is used to illustrate the steps.

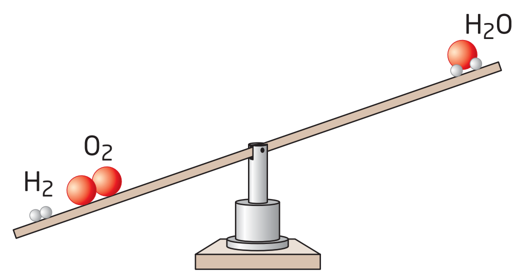
How to Balance a Chemical Equation

1. $H_2(g) + O_2(g) \rightarrow H_2O(\ell)$

In the skeleton equation, there is the same number of hydrogen atoms on both sides of the equation. There are more oxygen atoms in the reactants, however, than in the product.

Checking the Atom Balance

Element	Reactant	Product	Equal?
H	2	2	yes
O	2	1	no

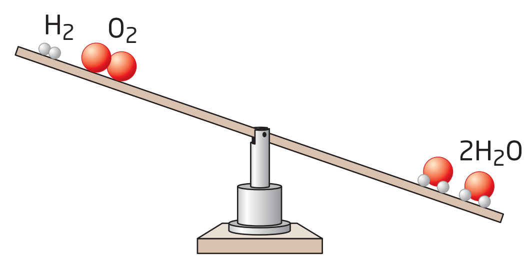


2. $H_2(g) + O_2(g) \rightarrow 2H_2O(\ell)$

Placing the coefficient 2 in front of H_2O causes the number of oxygen atoms on both sides of the equation to be the same. Because the coefficient applies to all the elements in the compound, however, it causes the number of hydrogen atoms in the product to increase to four.

Checking the Atom Balance

Element	Reactant	Product	Equal?
H	2	4	no
O	2	2	yes

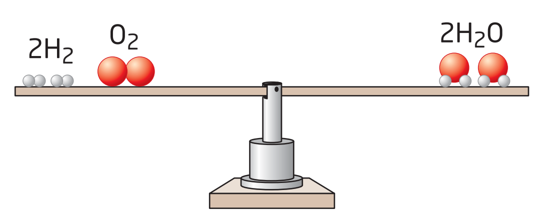


3. $2H_2(g) + O_2(g) \rightarrow 2H_2O(\ell)$

Placing the coefficient 2 in front of H_2 makes the number of hydrogen atoms on both sides of the equation equal again. The coefficient 2 applies only to H_2 on the left side because H_2 and O_2 are separate substances.

Checking the Atom Balance

Element	Reactant	Product	Equal?
H	4	4	yes
O	2	2	yes



Approaches to Balancing Chemical Equations

When you are balancing a chemical equation, it is important to remember that every equation is different. The same approach does not work for every chemical equation. You should be systematic, however, in the approach you use. A few suggestions to help you get started are listed below.

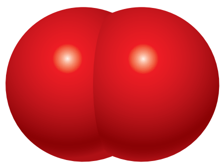


Figure 4.22 Oxygen exists as a diatomic molecule.

Tips for Balancing Chemical Equations

- Remember that these elements exist as diatomic molecules: hydrogen (H_2), nitrogen (N_2), fluorine (F_2), chlorine (Cl_2), bromine (Br_2), iodine (I_2), and oxygen (O_2), shown in **Figure 4.22**.
- Balance compounds first and elements last.
- Balance hydrogen and oxygen last. They often appear in more than one reactant or more than one product, so they are easier to balance after the other elements are balanced.
- If a polyatomic ion appears in both a reactant and a product, think of it as a single unit to balance the chemical equation faster.
- Once you think the chemical equation is balanced, do a final check by counting the atoms of each element one more time.
- If you go back and forth between two substances, using higher and higher coefficients, double-check each chemical formula. An incorrect chemical formula might be preventing you from balancing the chemical equation.

Learning Check

1. State three ways to represent a chemical reaction.
2. Why is the law of conservation of mass significant when writing chemical equations?
3. Determine the number of atoms of each element in the following.
   a. $2NaI$
   b. $3PCl_5$
   c. $2NaNO_3$
   d. $(NH_4)_2SO_4$
4. Balance each chemical equation.
   a. $Mg(s) + O_2(g) \rightarrow MgO(s)$
   b. $Li(s) + Br_2(g) \rightarrow LiBr(s)$
   c. $Al(s) + CuO(s) \rightarrow Al_2O_3(s) + Cu(s)$
   d. $CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$
   e. $Al(s) + O_2(g) \rightarrow Al_2O_3(s)$
   f. $CaCl_2(aq) + AgNO_3(aq) \rightarrow AgCl(s) + Ca(NO_3)_2(aq)$
5. Describe an everyday activity that requires a balancing process, similar to that of balancing a chemical equation.

Writing Balanced Chemical Equations

As you practise writing and balancing chemical equations, keep in mind the tips you have learned. Study the Sample Problem below, which discusses the production of ammonia, shown in **Figure 4.23**. Then try the Practice Problems that follow.

Sample Problem: Writing a Balanced Chemical Equation

Problem

Ammonia, $NH_3(g)$, is produced from the reaction of nitrogen gas and hydrogen gas. Write a balanced chemical equation for this reaction.

Solution

Begin by writing a word equation.

Word equation: nitrogen + hydrogen → ammonia

Next, write a skeleton equation by writing the chemical formula for each substance. Remember that nitrogen and hydrogen are diatomic molecules.

Skeleton equation: $N_2 + H_2 \rightarrow NH_3$

Finally, balance the equation using coefficients. Show the states of the products and reactants, if the information is provided.

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

Check Your Solution

Ensure that all chemical formulas are correct. Count the atoms of each element in the reactants and product to make sure the chemical equation is balanced.

Figure 4.23 Ammonia is an important fertilizer, and it is used in many household cleaners.

GRASP

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

Practice Problems

1. Write a word equation, a skeleton equation, and a balanced chemical equation for each chemical reaction. Include indications of state for all reactants and products in the balanced equation.
   a. A solid piece of magnesium reacts with oxygen gas to produce solid magnesium oxide.
   b. Iron reacts with oxygen to produce rust, Fe_2O_3.
   c. Nitrogen gas reacts with bromine gas to form gaseous nitrogen tribromide.
2. The combustion of methane gas, $CH_4(g)$, involves its reaction with oxygen to produce carbon dioxide gas and water vapour. Write the balanced chemical equation for this reaction.

Making a Difference

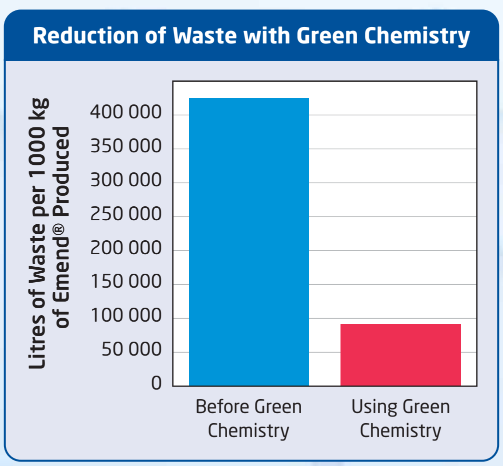
Adrienne Duimering was 14 years old when she saw statistics about fatal fires in Canada. Many of these fires could have been prevented. Adrienne wanted to know what products were available to help prevent fires. She discovered that fire retardants (chemicals used to fireproof flammable fabrics) can be expensive and toxic to the environment. Adrienne decided to investigate fire retardants for her 2007 Science Fair project. Her purpose was to find an inexpensive, environmentally friendly retardant. Adrienne tested the fire-retarding abilities of sodium bicarbonate (baking soda) and ammonium sulfate on common materials. She found that both compounds were effective fire retardants. Her project,"Fighting Flames Frugally," won a silver medal at the Canada Wide Science Fair. Adrienne has participated in the Vancouver Island Regional Science Fair since Grade 4. Her other projects have included investigations of the properties of insulators and ice-melters. Adrienne is now a Canada Wide Science Fair mentor and helps other students prepare for the competition.

Which products in your home could be replaced with safer, less expensive alternatives?

STSE Case Study

Green Chemistry

The development of new medicinal drugs has great benefits for humans and animals. The chemical reactions that are used to make these drugs, however, often involve many steps. These steps result in about 100 000 times more waste than the amount of drug produced, by mass. The waste can be harmful to the environment and expensive to dispose of.



The new reaction produces 340 000 fewer litres of waste per 1000 kg of drug produced. This is a significant reduction in waste; 340 000 L of waste could fill more than 2000 average-sized bathtubs.

A relatively new field of chemistry, called green chemistry, focusses on designing reactions that produce less waste. These reactions can be used for drug manufacturing and other industrial processes. Green chemistry also focusses on reducing or eliminating toxic substances that are used in or produced by many chemical reactions.

Green Medicine

For example, Merck and Co., Inc. has developed a greener reaction for synthesizing its drug Emend®. Emend® is used to treat vomiting and nausea caused by chemotherapy. The new reaction is far more efficient than the original reaction. It uses smaller amounts of reactants, water, and energy, but results in twice as much of the desired product. It also involves fewer steps than the original reaction. In addition to the environmental benefits of the new reaction, the production costs have decreased.

In the past, chemists who were working to help the environment focussed on ways to clean up the toxic wastes that were produced by chemical processes. The aim of green chemistry is not to create these toxic wastes in the first place.

Practical Uses of the Conservation of Mass

The principles of the conservation of mass have many practical applications. Sometimes, a toxic chemical spill is cleaned up by adding another chemical, as shown in **Figure 4.24**. Care must be taken to make sure that all the toxic chemical has reacted and none remains. If the reactant that is used for the clean-up might also harm people or damage the environment, it is important to calculate the exact amount needed, so that none remains. Calculating the exact amount of a reactant relies on an understanding of the law of conservation of mass.

Figure 4.24 A chemical is being applied to an oil spill test tank to determine how efficient it is in breaking up the oil.

Industrial chemistry relies very heavily on using the proper amounts of reactants to obtain a desired product. A great deal of time, effort, and money is put into optimizing industrial chemical processes to minimize the waste of expensive materials. Also, any excess materials may become waste that needs to be discarded. This can be problematic if this waste material is at all toxic or harmful for the environment.

Your Turn

1. Conduct on-line research to identify the 12 principles of green chemistry.
2. Choose one principle of green chemistry. Explain how this principle helps to protect the environment.
3. Initially, a company has to spend time and money to make its manufacturing process greener. You are an environmental consultant who must convince chemical companies to switch to green chemistry. Prepare a presentation highlighting why green chemistry is worth the investment.

What Makes a Chemical Reaction Green?

Some of the principles of green chemistry include

- preventing waste
- using safer solvents
- using renewable raw materials
- ensuring that reactions are energy efficient

Atom economy (AE) is an important principle of green chemistry. Chemists design reactions to use as little of the reactants as possible to produce the greatest yield of the desired product, and thus reduce waste. They calculate percent atom economy using this equation.

$$\%AE = \left(\frac{\text{mass of final desired chemical compound}}{\text{sum of masses of all reactant compounds}}\right) \times 100\%$$

Section 4.3 Review

Section Summary

- The law of conservation of mass states that the total mass of the reactants must equal the total mass of the products in a chemical reaction.
- A chemical reaction can be represented by a word equation, in which the names of the reactants and products are shown, or by a skeleton equation, in which the chemical formulas of the reactants and products are shown.
- A balanced chemical equation has coefficients in front of the chemical formulas. The number of atoms of each element is the same in the reactants and the products.
- An understanding of the law of conservation of mass can be applied to the clean-up of hazardous materials and the manufacture of products, to reduce potential harm or waste.

Review Questions

T/I **1.** A student carries out a reaction in which one product is a gas. If the student does not collect the gas, how will the mass of the reactants compare with the mass of the products? Explain.

A **2.** The photograph on the right shows a piece of magnesium metal in a solution of hydrochloric acid, HCl(aq). A solution of magnesium chloride and a gas are produced. What element do you expect the gas to be? Explain your reasoning, using the law of conservation of mass.

Magnesium reacts with aqueous hydrochloric acid.

K/U **3.** How many atoms of each element are in the following?

a. $2FeI_3$

b. $3Ca(OH)_2$

c. $3Ca(NO_3)_2$

d. $3NH_4ClO_4$

C **4.** Use a flowchart to describe how you would write a word equation to represent a chemical reaction.

K/U **5.** What does an addition sign mean in a chemical equation?

K/U **6.** What are the four abbreviations that are used to show the states of substances in chemical reactions?

T/I **7.** State whether each chemical equation is balanced. If an equation is not balanced, identify the elements that are not balanced and then balance them.

a. $Al(s) + 3F_2(g) \rightarrow 2AlF_3(s)$

b. $Ca(OH)_2(aq) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(\ell)$

c. $2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(g)$

d. $K_2SO_4(aq) + 2AgNO_3(aq) \rightarrow Ag_2SO_4(s) + KNO_3(aq)$

K/U **8.** When solid sodium carbonate is heated, it changes into solid sodium oxide and carbon dioxide gas. Write the word equation, the skeleton equation, and the balanced chemical equation for this reaction.