Key Terms
neutralization
liming

6.3 Reactions of Acids and Bases

In 1971, astronauts from the United States trained near Sudbury, Ontario, for an Apollo mission to the Moon. This site was chosen because of the presence of rare rock formations called *shatter cones* that form from meteorite impacts. At the time, the land around Sudbury was quite desolate and barren, as shown in **Figure 6.15A**. This prompted many people to believe that the astronauts were training there because the land resembled the barren, lifeless surface of the Moon. Scientists determined that much of the damage to the environment was caused by acid precipitation, which was the result of gas emissions from local smelters. Smelters are industrial facilities in which metals are separated from ores.

The realization of the widespread damage caused by smelter emissions led the governments of Canada and the United States to agree to decrease the emissions. Principles of acid-base chemistry were applied to help counter the effects of acid precipitation. In addition, efforts such as tree planting initiatives by local communities and Aboriginal peoples have helped to improve the land around Sudbury, as shown in **Figure 6.15B**.

Figure 6.15 **A** The land around the Sudbury smelters was badly damaged from smelter emissions and acid precipitation. **B** Efforts that reduced emissions by 90 percent over the last 30 years have given the area a chance to recover.

Acid-Base Neutralization

When an acid and a base are mixed, they react and can neutralize each other. **Neutralization** is the reaction of an acid and a base to form a salt and water. For example, hydrochloric acid and sodium hydroxide react as shown in the balanced chemical equation

$$\mathbf{H}Cl(aq) + Na\mathbf{OH}(aq) \rightarrow \mathbf{H_2O}(\ell) + NaCl(aq)$$

You might recognize this type of reaction as a double displacement reaction in which the ions of the reactants switch places to form new compounds. The water forms as the hydrogen ions of the acid and the hydroxide ions of the base combine.

$$H^+(aq) + OH^-(aq) \rightarrow HOH(\ell)$$

The other ions join to form a salt. In this reaction, the salt formed is sodium chloride, or table salt. However, any ionic compound that is neither an acid nor a base can be called a salt. In most cases, the salt formed by a neutralization reaction is soluble in water and will not form a precipitate.

Whether the acid is added to the base or the base is added to the acid, the removal of both hydrogen ions and hydroxide ions from solution as they form molecules of water causes the pH of the mixture to approach 7. If the right amounts of acid and base react, the resulting solution will be neutral.

neutralization the reaction of an acid and a base to produce a salt and water

Suggested Investigation

Inquiry Investigation 6-C, Neutralizing an Acid with a Base, on page 250

An Application of Neutralization: Antacids

The pits in the lining of your stomach, shown in **Figure 6.16**, secrete hydrochloric acid. This acid helps to break down food in the digestion process. A problem that many people suffer from is excess production of acid. This can result in heartburn, which includes a burning sensation in the stomach that can extend up through the chest area into the esophagus or throat. A common treatment for heartburn is the use of commercially available *antacids*. As their name implies, antacids are designed to neutralize the acid. They have an ingredient that is a base to help increase the pH of the gastric juices of the stomach. Common bases used in antacids are magnesium hydroxide and aluminum hydroxide.

Figure 6.16 This photograph of the lining of the stomach, at about 700 times magnification, was taken using an electron microscope. Acids are secreted into the stomach from gastric pits (dark holes). These acids are needed for digestion.

Neutralizing Acid Spills

In late March 2007, railroad tanker cars derailed, as shown in **Figure 6.17**. The accident spilled 150 000 litres of sulfuric acid into the Blanche River near Englehart, Ontario. An important step in the clean-up was adding a base, calcium hydroxide to the river to help neutralize the acid:

$$H_2SO_4(aq) + Ca(OH)_2(aq) \rightarrow CaSO_4(aq) + 2H_2O(\ell)$$

When an acid spill occurs, a quick response is critical. It is important to minimize the size of the spill by containing the spilled acid and stopping any leaks from containers such as overturned tankers. Neutralizing the acid and warning or evacuating people in the area helps to prevent injuries. Cleaning up the spill does not prevent harm to the environment, however. Following the spill near Englehart, dead fish washed up on the banks of the river as a result of acidic water.

Learning Check

1. Define neutralization and give one example of a neutralization reaction.
2. Draw a graphic organizer that identifies the reactants and products of a neutralization reaction.
3. Why is neutralization important in cleaning up an acid spill?
4. With your teacher, examine the contents of the spill kit in your classroom laboratory. Which materials in the kit should be used if an acid spill occurs? if a base spill occurs? Explain how these materials work.

Figure 6.17 Sulfuric acid leaked from these tankers after they derailed near Englehart, Ontario. Residents in the area were warned not to use river water until the clean-up was complete.

Acid Precipitation

Rainwater is naturally acidic and normally has a pH of around 5.6. This acidity is the result of carbon dioxide in the air dissolving in and reacting with water to form carbonic acid:

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

However, similar synthesis reactions of other non-metal oxides form additional acids, which lower the pH of rainwater even further.

Causes of Acid Precipitation

As you have already learned, the high temperature in a car's engine causes nitrogen and oxygen to react and form several oxides of nitrogen, represented as NO_x. These oxides can react with water to form acids. For example, nitrogen dioxide reacts with water to produce nitric acid:

$$NO_2(g) + H_2O(\ell) \rightarrow HNO_3(aq)$$

Catalytic converters help to decrease the amount of nitrogen oxides that enter the atmosphere, but do not eliminate the NO_x emissions completely. In Canada, the main source of NO_x emissions is the transportation sector. Since 1985, NO_x emissions have remained relatively constant.

Another major contributor to acid precipitation is sulfur oxides, represented as SO_x. Sources include industrial processes. For example, ores smelted in the Sudbury region contained sulfur, which forms sulfur dioxide during the smelting process. This gas is also produced during the combustion of fossil fuels that contain sulfur. Coal and natural gas contain some sulfur or sulfur compounds that can form sulfur dioxide when combusted.

$$S_8(s) + 8O_2(g) \rightarrow 8SO_2(g)$$

The sulfur dioxide can react with additional oxygen to form sulfur trioxide, which in turn can react with water to form sulfuric acid:

$$2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$$

$$SO_3(g) + H_2O(\ell) \rightarrow H_2SO_4(aq)$$

As you can see in **Figure 6.18**, more than 95 percent of sulfur dioxide emissions in Canada come from industrial sources and electric utilities. Under the initiation of the Canada-Wide Acid Rain Strategy and Eastern Canada Acid Rain programs, Canada experienced a reduction in sulfur dioxide emissions of approximately 50 percent.

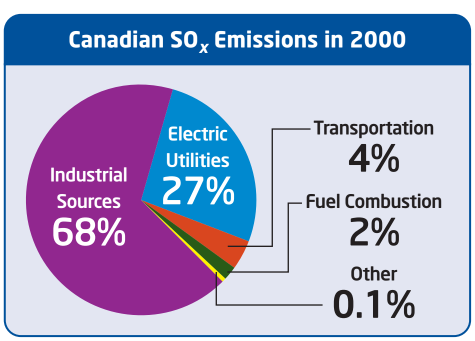


Figure 6.18 The biggest potential for reducing SO_x emissions in Canada occurs in industrial plants and electric utilities.

Sense of place

In Canada's western Arctic, about a kilometre south of the Beaufort Sea, are the Smoking Hills. These sea cliffs contain carbon-rich shale and sulfur-rich pyrite that have been burning for centuries. Limestone in the area causes lakes to have a pH above 8.0. However, the acid precipitation that has resulted from the smoke from these hills has lowered the pH of some lakes to below 2.0.

Effects of Acid Precipitation

Figure 6.19 The spring snowmelt can carry a large amount of acid that had been trapped in the snow and ice. This can cause a sharp drop in pH in nearby lakes.

Eastern Canada is especially sensitive to the effects of acid precipitation. In provinces that are part of the Canadian Shield, such as Ontario, the soils and waterways lack a natural ability to fight the damage caused by acid precipitation. These areas contain mostly granite rock, which does not provide a natural source of basicity. Other areas, such as western Canada, contain more limestone-based rock, which does have a natural basicity. As a result, soils in these areas can help to neutralize the acid precipitation and, therefore, reduce its effects.

Effects of Abrupt Changes in Water pH

In some instances the change in pH of the lake or river water can be abrupt. The rushing waters of the snowmelt in **Figure 6.19** could hold a deadly dose of acid for fish in a nearby lake or stream. Mass fish kills can occur in the spring because acidic pollutants that have collected in the snow start to drain into these bodies of water. However, more often, fish gradually disappear from a lake or a stream as the environment slowly becomes less tolerable.

STSE Case Study

Update on Acid Precipitation

Scottish chemist Robert Angus Smith first described acid precipitation during the Industrial Revolution of the 19th century, when coal-powered factories that released huge amounts of pollution became common. Acid precipitation or, technically, "acid deposition" includes acidic rain, snow, sleet, hail, and fog. Acid precipitation comes from emissions from power plants, factories, motor vehicles, and even volcanoes. Acid precipitation affects terrestrial and freshwater ecosystems, in addition to human health.

Acid Precipitation in North America

In North America, scientists reported acid precipitation effects mainly in provinces east of Manitoba and in the northeastern United States. In general, the locations were downwind from major industrial polluters, and less able to neutralize acid precipitation naturally, compared to other locations.

For example, the area around Killarney, Ontario, suffered from air pollution coming from the United States and from Sudbury metal smelters 50 km away. Killarney's Canadian Shield bedrock and coniferous forests in shallow, acid soils could not neutralize the acid precipitation. Similarly, Nova Scotia ecosystems cannot easily neutralize acid precipitation, so some of its rivers can no longer support salmon.

Effects of Gradual Changes in Water pH

A healthy lake or stream can support a greater variety of organisms than an acidified one. **Table 6.7** shows the changes in lake organisms that occur as the water's pH decreases. As a lake or stream becomes more acidic, many types of tiny organisms start to disappear. These organisms are food sources for fish and other animals. In addition, as the pH decreases, fish have trouble reproducing. A decrease in fish populations affects animals that depend on fish as a food source. For example, populations of loons, shown in **Figure 6.20**, and other water birds decrease when there are not enough fish to support them.

Go to **scienceontario** to find out more

Figure 6.20 An increase in the acidity of a lake can cause a decrease in water bird populations, such as loons.

Table 6.7 Changes to a Lake at Various pH Values

pH	Effects
6.0	• some insects, plankton, and crustaceans die
5.0	• large change in the variety of plankton • invasion by less desirable species of plankton and moss • loss of some fish populations
< 5.0	• few fish remain • land animals are affected by the loss of fish

Taking Action

Countries have taken action to reduce the effects of acid precipitation. For example, Canada and the United States signed the *Canada-U.S. Air Quality Agreement* in 1991. Canada also devised national pollution-reduction goals. Since then, Sudbury industries have reduced air pollution by 90 percent, and many lakes in the Killarney region are now less acidic and much healthier than before.

Since the signing of a 1991 agreement, many lakes in the Killarney region have undergone varying degrees of recovery.

Despite these efforts, some ecosystems are still receiving levels of acid precipitation that they cannot tolerate. And even ecosystems that get less acid precipitation may not simply rebound. Acid deposition may not be in the news a lot these days, but it is still a major environmental issue in many countries.

Your Turn

1. Identify the factors that contribute to acid deposition.
2. Research one technology for reducing air pollution and discuss it with a small group.
3. Research one of the following approaches for reducing the effects of acid deposition and present your information to the class:
   a. adding lime to acidic lakes in Sweden
   b. adding more acid-tolerant fish species to recovering Killarney, Ontario, lakes

Making a Difference

Simon Bild-Enkin has combined his interest in science and history to complete unique science fair projects. In Grade 10, he researched the effects of acid precipitation on historic buildings. Many buildings are made from limestone. Acid precipitation damages these buildings because limestone dissolves in acid. Simon investigated the effects of different concentrations of acid on limestone. He also tested the use of a protective coating of paraffin wax on the limestone. He found that higher concentrations of acid dissolved more limestone, and that a protective coating was helpful only if applied perfectly. Upon completing his experiments, Simon concluded that the best way to preserve buildings is to reduce the effects of acid precipitation by dealing with its causes.

Simon won third place at the Vancouver Island Regional Science Fair and presented his project at the 2007 Canada Wide Science Fair.

How could you contribute to initiatives to reduce the harmful effects of acid precipitation?

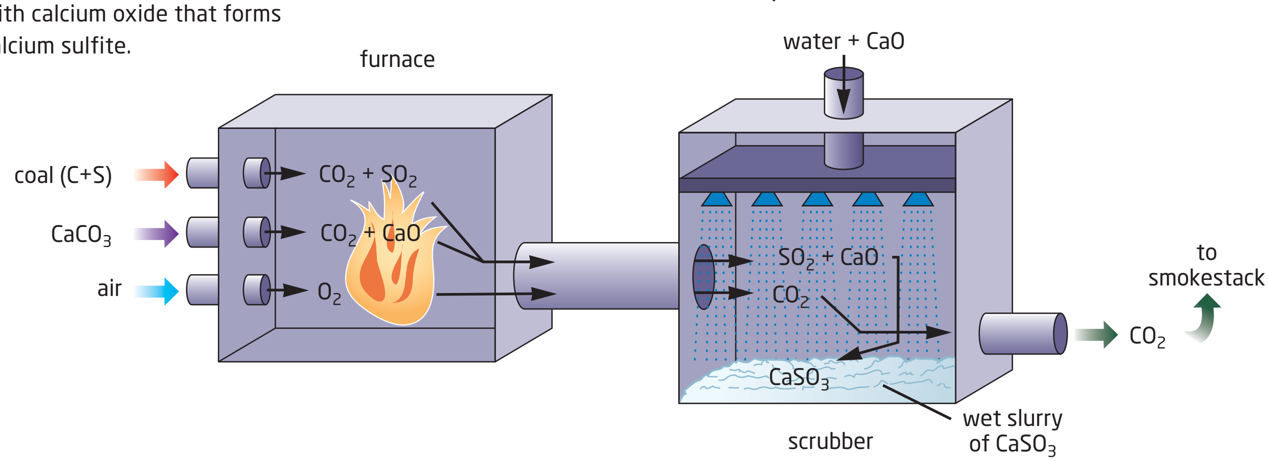
Reducing Emissions That Cause Acid Precipitation

Through a better understanding of the properties of chemicals and the reactions associated with them, scientists know more about acid precipitation and the problems it causes. Now, scientists are working to apply this understanding to help solve the environmental challenges caused by acid precipitation. One solution is to reduce the emissions that cause acid precipitation.

Sulfur oxides are a major contributor to acid precipitation. One way to reduce sulfur oxide emissions is to use *scrubbers* on smokestacks of industrial plants that burn coal in their furnaces, as shown in **Figure 6.21**. Nearly all sources of coal contain sulfur as a contaminant. When the coal burns, the sulfur contaminant also burns, forming sulfur dioxide (SO_2), as discussed on page 239.

Calcium carbonate ($CaCO_3$) is added to the coal and air as they enter the furnace. While the coal burns in air, it forms CO_2 and SO_2 gases. The $CaCO_3$ decomposes into CO_2 and CaO. Some of the SO_2 reacts with the CaO, forming calcium sulfite ($CaSO_3$). Unreacted SO_2 enters the wet scrubber, where a slurry of CaO in water is sprayed. Most of the remaining SO_2 reacts with the dissolved CaO, forming $CaSO_3$, which mixes with water to form a slurry that is discarded.

Figure 6.21 To reduce emissions that could form acid precipitation, sulfur dioxide is removed from exhaust gases through a reaction with calcium oxide that forms calcium sulfite.



Renewing Acidified Lakes

Another way to address acid precipitation is to attempt to reverse its effects. For example, **Figure 6.22** shows a helicopter treating an acidic lake. The process, called **liming**, is like giving the lake a giant crushed antacid tablet. The calcium carbonate that is added to the lake is the active ingredient in many antacids. The calcium carbonate reacts with the acid and raises the pH of the water.

liming the application of basic materials, typically lime-based, to renew acidified lakes and regions

Effects of Liming on Lakes

Why isn't liming used to renew all lakes that have become too acidic? If liming a lake once could correct the problem for good, then it might be possible (over a long time and at great expense) to renew all acidic lakes. However, as long as acidic water continues to enter the lake, the pH will drop again and the lake will require additional treatments.

In addition, liming can cause problems. Adding limestone to a lake increases the calcium content of the water. Some species, such as the bog moss sphagnum and some types of insects, are sensitive to calcium levels. Preventing acid precipitation by using catalytic converters, scrubbers, and new technologies is a much better solution.

Suggested Investigation

Real World Investigation 6-B, The pH of Lakes Near Sudbury, on page 248

Figure 6.22 Adding limestone to an acidic lake helps to renew the lake and raise its pH. However, if the source of the acid is not eliminated, treatments must be repeated at intervals to maintain the higher pH.

Learning Check

5. What is the pH of normal rainwater?
6. Based on the data in **Figure 6.18**, what percentage of SO_x emissions comes from industrial sources?
7. Make a drawing that shows the sources of gases that cause acid precipitation and identifies the technologies that are used to reduce each emission.
8. How is liming a lake similar to a doctor prescribing medicine for a patient?

Activity 6-4

Air Pollution and Ontario's Lakes

Gases produced by combustion in our cars, homes, and industries are released directly into Earth's atmosphere. What effect do these gases have on our lakes? In this activity, you will create some gases, observe their effect on Lake Erlenmeyer, and then attempt to neutralize the effect.

Safety Precautions

- Wear safety goggles and a lab apron.
- Be very careful with the open flame.

Materials

- water
- two 250 mL Erlenmeyer flasks
- universal indicator solution
- wooden safety match
- tongs
- stopper
- chalk dust

Procedure

1. Put about 50 mL of clean water into a 250 mL Erlenmeyer flask, and add 10 drops of universal indicator. This is flask A.
2. Working with a partner, one of you holds the second flask upside down. The other partner lights the match and, gripping it with tongs, places the lit end of the match into the flask. When the match head has finished flaring, remove the match and stopper the flask. You have trapped some gases from combustion. This is flask B.
3. Turn flask B right side up, open the stopper, and quickly pour the water and indicator from flask A into flask B. Replace the stopper, and shake gently for one minute.
4. Open the stopper, and add a generous pinch of chalk dust. Replace the stopper, shake vigorously, and let stand.

Questions

1. When the match head burns, sulfur, phosphorus, and carbon in the match head join with oxygen to form new chemical compounds. Propose some names for the gases produced.
2. What is the pH of the solution formed when the combustion products are dissolved in the water? What kind of solution must this be?
3. Crushed limestone or chalk, which are composed of calcium carbonate, is often added to acidified lakes to neutralize the acid. Does the addition of powdered chalk change the pH? Is this a fast or slow process?

Acid Leaching and Metals

Smelters, such as those at Sudbury, create acids as a by-product of the smelting process. However, acids are also an important part of refining metals. In Chapter 5, you learned how gold is leached from its ore using sodium cyanide. For other metals, such as copper and nickel, acids are used in the refinement process. The acid reacts with the metals and forms soluble compounds. The acidic solution containing the soluble metal salt is separated from the unwanted solid materials and the metals are later recovered from the solution. Although the properties of acids and of metals allow acid leaching to be used to extract these desirable metals from their ores, these same properties create environmental problems.

Toxic Metal Contamination and Clean-Up

At many mining sites, you can see tailings piles, such as those in **Figure 6.23**. Tailings are the materials, both solid and liquid, that are left after the desired product, such as copper, nickel, or gold, is removed from an ore. These piles are often stored in above-ground facilities, where they are exposed to air and water.

Sulfide compounds in the tailings can form acids as they react with water and oxygen. If not contained, the resulting acids could cause run-off that can harm the local environment. The acids can also leach metals from the tailings, which could contaminate the area around the tailings pile.

Acid leaching can actually be used to clean up soils that have been contaminated by toxic metals. A diagram of the process used is shown in **Figure 6.24**. The first step is to remove any solid metal pieces from the contaminated soil, which reduces the amount of acid needed to treat the soil. The metal removed can be sent to a smelter to be melted down. The soil is then treated with acid in order to leach out metal ions and any small pieces of metal. Once the metal has been dissolved in the acid, it is recovered through precipitation. Chemicals that form solid precipitates with the metal ions are added to the solution. After precipitation, the liquid component is recycled and used in the leaching process again, while the solid component that contains the metal is collected for appropriate disposal. Nevertheless, the process is expensive. Therefore, preventing contamination in the first place is the best solution to the problem.

Figure 6.23 The materials left over from the processing and recovery of a metal can be a source of pollution as a result of reactions of acids. These tailings piles are from a gold mine near Dawson, in the Yukon.

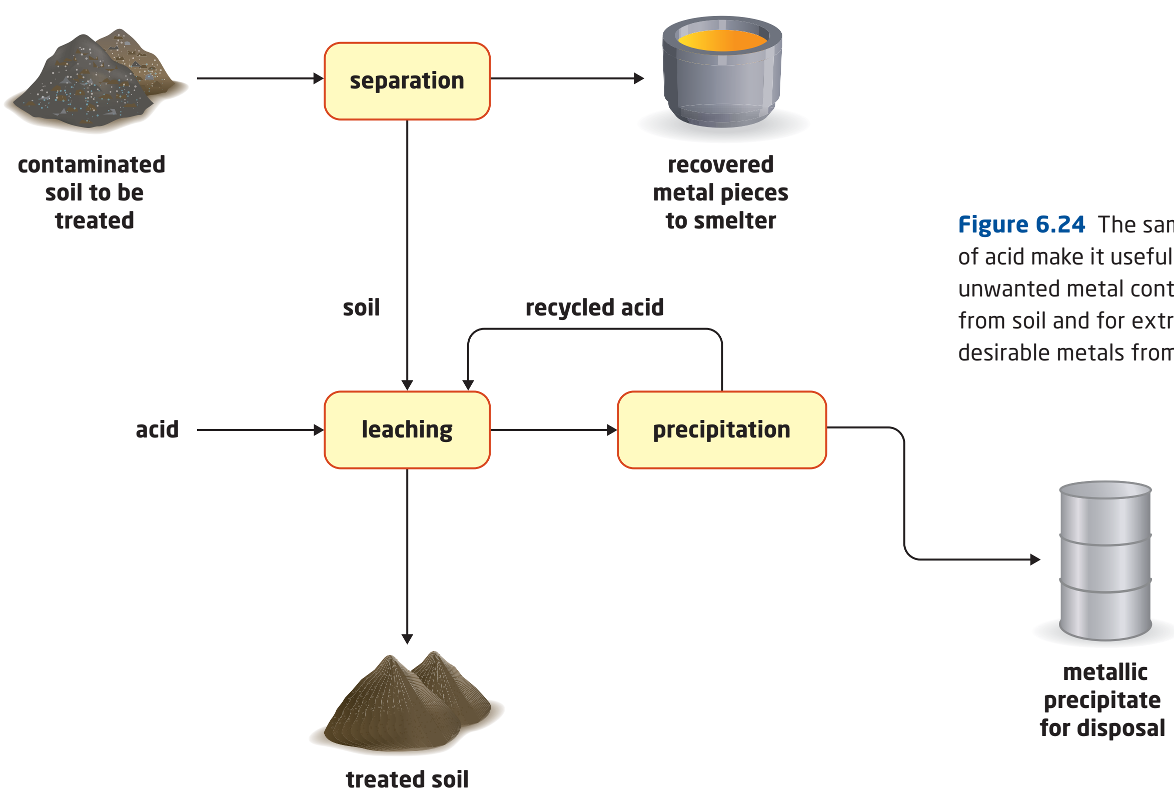


Figure 6.24 The same properties of acid make it useful for removing unwanted metal contaminants from soil and for extracting desirable metals from ores.

Section 6.3 Review

Section Summary

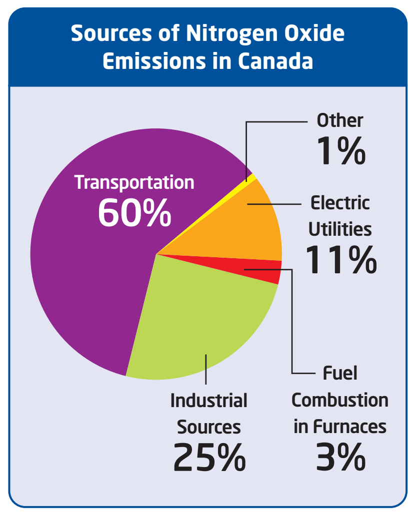
- A neutralization reaction occurs when an acid and a base react to form water and a salt.
- Acid precipitation forms from non-metal oxides, such as the oxides of sulfur and of nitrogen. These oxides in the atmosphere react with water to form acids. Scrubbers are used to remove sulfur dioxide from exhaust gases.
- Acid precipitation can have detrimental effects, particularly on rivers and lakes. Renewing a lake involves adding limestone to the water to help neutralize the acid and raise the pH.
- The properties of acids make them useful for extracting metals from ores, but the process may contaminate an area. These same properties also mean that acids are useful for leaching toxic metals from contaminated soils.

Review Questions

K/U **1.** Write a balanced chemical equation for the neutralization of sulfuric acid with potassium hydroxide. What is the name and chemical formula of the salt formed in this reaction?

K/U **2.** When you have an upset stomach, you might take an antacid to feel better. Based on the properties of an antacid, explain why an antacid can be an effective remedy.

T/I **3.** Describe how nitrogen oxides contribute to acid precipitation and name a technology that is used to reduce these emissions. Based on the data in the graph on the right, what percentage of nitrogen oxide emissions are from industrial sources?



K/U **4.** What gas reacts with water to form sulfuric acid?

K/U **5.** List two changes that occur in the populations of organisms in a lake at pH 5.0.

C **6.** Make a pamphlet that explains the process of scrubbing smokestack emissions and the reactions associated with it. Research industries in which this technology is used, and suggest some additional industries that could use it.

A **7.** Some fish populations suffer from a condition caused by high levels of aluminum in the water. Explain why acid precipitation might be a cause of this problem.

C **8.** Provide an argument that counters the idea that acid precipitation is no longer a problem in Ontario.