10.6 Corrosion

There are an estimated 9000 shipwrecks corroding on the seabed (**Figure 1**). About one-sixth of these vessels are oil tankers that were sunk during World War II. As the steel in the hulls of these ships corrodes, the oil will leak and pollute local ecosystems. In this section, you will examine corrosion, its causes, and how it can be prevented.

Figure 1 A diver peers through the rusty porthole of a sunken ship.

The Oxidation of Metals

corrosion the deterioration of a metal by a redox reaction

You can consider corrosion to be the process of metals returning to their natural state—the ores from which the metals were originally obtained. **Corrosion** can be defined as the breakdown or deterioration of a metal by a redox reaction. Since corroded metal often loses its strength and attractiveness, this spontaneous process has a great environmental and economic impact. Approximately one-fifth of the iron and steel that is produced annually is used to replace rusted metal. Although steel is infinitely recyclable, replacing corroded steel and iron uses additional resources and energy. WEB LINK

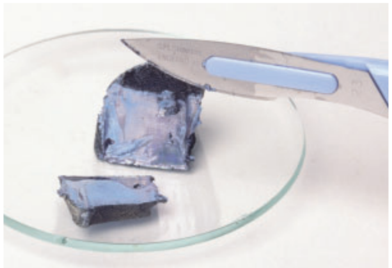

Figure 2 A freshly cut piece of sodium metal reacts almost instantly with oxygen to form dull-grey sodium oxide, $Na_2O(s)$.

Metals corrode because they oxidize easily. With the exception of gold, all the metals that are commonly used for structural and decorative purposes have standard reduction potentials below (less positive than) the reduction potential of oxygen gas. (Refer to the Standard Reduction Potentials table in Appendix B7.) When the half-reaction for any of these metals is reversed (to show the oxidation of the metal) and combined with the reduction half-reaction for oxygen, the result is a positive $E°_r$ value. Thus, the oxidation of most metals by oxygen is spontaneous. We cannot, however, tell from the reduction potential how fast the oxidation will occur (**Figure 2**).

Considering the large difference between the reduction potentials for oxygen and most metals, it is rather surprising that the problem of corrosion in air does not completely prevent us from using metals. With a reduction potential of −1.66 V, for example, aluminum should be easily oxidized by $O_2(g)$. Based on aluminum's low reduction potential, an aluminum airplane should dissolve in a rainstorm. Why, then, is this very active metal used as a structural material? The reason is due to a thin, adherent layer of aluminum oxide, $Al_2O_3(s)$, that forms on the surface of the aluminum. This layer protects the internal atoms from further oxidation. Iron also forms an oxide coating when exposed to oxygen in moist air. However, unlike the oxide that forms on aluminum, the resulting oxide does not adhere well to the underlying metal. As a result, the oxide flakes off and exposes new metal to corrosion. This is why iron and steel are so seriously affected by corrosion, or rust. CAREER LINK

Investigation 10.6.1

Testing the Corrosion of Iron **(page 674)**
In this controlled experiment, you will test the effects of several factors on the corrosion of iron.

The corrosion products of "noble" metals, such as copper and silver, are complex and affect the use of these metals as decorative materials. Under normal atmospheric conditions, copper forms a layer of greenish copper carbonate (**Figure 3**). Silver tarnish is black silver sulfide, $Ag_2S(s)$. Gold does not corrode in air because it has a positive standard reduction potential of 1.50 V, greater than that of oxygen (1.23 V).

Figure 3 The green colour of copper carbonate, sometimes called verdigris, can be clearly seen on the copper rooftop of the Peace Tower at the Parliament Buildings in Ottawa.

Rusting: The Corrosion of Iron

Steel is a metal alloy that is composed mainly of iron, with a small percentage of carbon. Depending on the type of steel and the intended application, other small percentages of other elements are also included in the steel alloy, such as manganese, vanadium, chromium, and nickel. Stainless steel is an exception. Stainless steel may contain up to 18 % chromium and up to 10 % nickel.

Since steel is the main structural material for bridges, buildings, and automobiles, and iron is a large component of steel, controlling the corrosion of iron is extremely important. Instead of being a direct oxidation process, the processes that occur as iron corrodes are similar to those in a galvanic cell. The corrosion of iron is an electrochemical process (**Figure 4**).

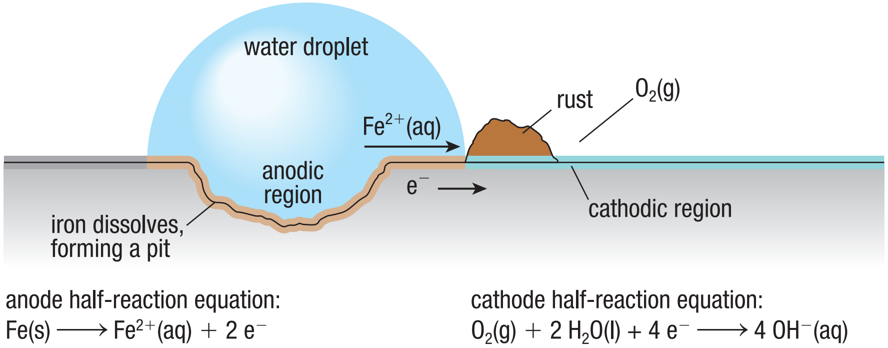

Figure 4 The electrochemical corrosion of iron

The chemical composition of steel is not quite homogeneous. It has a slightly non-uniform surface. As well, bending the steel causes physical strains and leaves stress points in it. The iron is more easily oxidized at these non-uniformities and stress points (anodic regions) than it is in other parts of the steel (cathodic regions). In an anodic region, each iron atom gives up two electrons to form an iron(II) ion:

$$Fe(s) \rightarrow Fe^{2+}(aq) + 2\,e^-$$

The electrons that are released flow through the steel, as they do through the wire of a galvanic cell, to a cathodic region. At the cathodic region, they are involved in the reduction of oxygen:

$$O_2(g) + 2\,H_2O(l) + 4\,e^- \rightarrow 4\,OH^-(aq)$$

The iron(II) ions that are formed in the anodic region travel to the cathodic region through the moisture on the surface of the steel, just as ions travel through a salt bridge in a galvanic cell. In the cathodic region, iron(II) ions react with oxygen to form rust. Rust is a hydrated form of iron(III) oxide, $Fe_2O_3{\bullet}nH_2O(s)$, where n can vary depending on the conditions for the reaction.

Because of the migration of ions and electrons, rust often forms some distance away from where the iron was oxidized. The degree of hydration of the iron oxide affects the colour of the rust, which may vary from black to yellow to the familiar reddish brown.

The electrochemical nature of the corrosion of iron explains the importance of moisture in the corrosion process. Water is a reactant in the reduction half-reaction. It also acts much like a salt bridge in a galvanic cell, connecting the anodic and cathodic regions. Steel does not rust in dry conditions, which explains why vehicles remain corrosion-free in dry climates (**Figure 5**).

Figure 5 Hundreds of old airplanes are stored at this airplane graveyard in Arizona, U.S., until they can be stripped of any usable parts. The dry desert air prevents the airplanes from rusting.

Salt does not actually cause corrosion. However, salt definitely accelerates corrosion by providing ions—much like the salt bridge in a galvanic cell. Vehicle owners in regions of Canada where salt is used on roads to melt snow and ice are very aware of this fact. The severity of rusting is greatly increased because the dissolved salt on the moist steel surface increases the conductivity of the aqueous solution formed, and thus accelerates the electrochemical corrosion process.

Corrosion Prevention

Preventing corrosion is an important way to conserve energy and metals. The primary method of prevention is the application of a coating, such as paint, to protect the metal from oxygen and moisture. The metal remains protected as long as the coating remains intact. However, even a tiny pinhole in the coating could become a corrosion site.

galvanizing the process in which steel is coated with a thin layer of zinc to protect the steel from corrosion

Plating steel with other metals provides longer-lasting protection than painting. Chromium and tin are often used to plate steel because they oxidize to form a durable, effective oxide coating. In a process called **galvanizing**, zinc is also used to coat steel. Zinc forms a mixed oxide–carbonate coating (**Figure 6**).

Since zinc is a more active metal than iron, any oxidation that occurs involves zinc rather than iron. Consider the reduction half-reaction potentials for iron and zinc:

$$Fe^{2+}(aq) + 2\,e^- \rightarrow Fe(s) \quad E°_r = -0.44\text{ V}$$

$$Zn^{2+}(aq) + 2\,e^- \rightarrow Zn(s) \quad E°_r = -0.76\text{ V}$$

Recall that the strongest reducing agents are near the bottom of the right side of the standard reduction potentials table. Therefore, zinc is a stronger reducing agent than iron, so it is oxidized before iron. Once zinc is oxidized, its oxide–carbonate coating clings tightly to the iron beneath it, isolating iron from the environment. Unlike painting, galvanizing continues to provide corrosion protection even if the metal surface is scratched.

Alloying, the process of combining two or more metals, is also used to prevent corrosion. Stainless steel, as noted earlier, contains chromium and nickel. Both of these metals form oxide coatings that help the steel resist corrosion. In some applications, such as surgical implants, it is critical that the metals do not corrode (**Figure 7**).

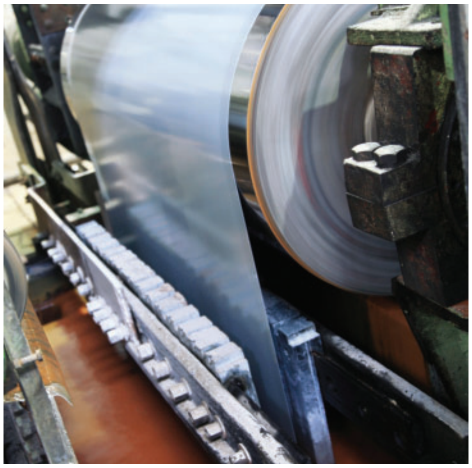

Figure 6 Steel is galvanized by rolling it through a solution of zinc ions. As electricity is passed through the solution, zinc is deposited on the surface of the steel, galvanizing it.

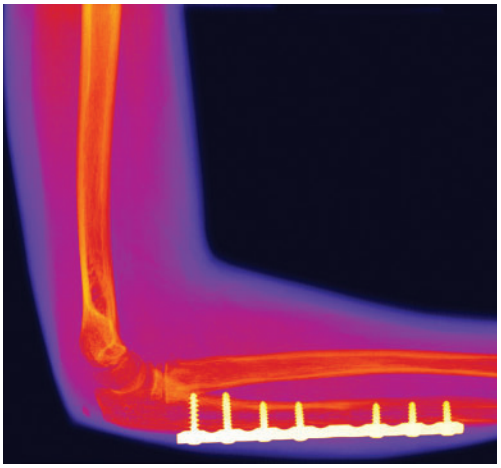

Figure 7 This coloured X-ray image of an arm shows how the ulna was repaired using a surgical-steel implant secured with screws.

cathodic protection a form of corrosion prevention in which electrons are continually supplied to the metal that is being protected, making the metal a cathode

Cathodic protection is the most common form of corrosion prevention for steel in buried fuel tanks and pipelines. The two methods that are used to provide cathodic protection are the sacrificial anode (active metal) method and the impressed current method. Both methods work the same way—by supplying the metal to be protected with electrons so that it cannot be oxidized. As a result, the metal becomes the cathode of the corrosion cell.

The **sacrificial anode** method involves attaching a more active metal, such as magnesium, to the steel. The active metal is connected by a wire to the pipeline or tank that needs to be protected (**Figure 8(a)**). This method may be used in your home to protect the water heater from corrosion. Since the magnesium is a better reducing agent than iron, electrons are supplied by the magnesium rather than the iron, keeping the iron from being oxidized. As oxidation occurs, the magnesium anode is used up, so it must be replaced periodically. The hull of a ship may be protected in a similar way, by attaching bars of zinc to the steel hull. In salt water, the zinc acts as the anode and is oxidized instead of the steel hull (the cathode).

sacrificial anode a form of cathodic protection in which the oxidation of a more active metal that is attached to the steel prevents the iron in the steel from being oxidized

The **impressed current** method involves attaching the object to be protected to the negative terminal of a DC power supply (**Figure 8(b)**). An inert electrode, such as graphite, is attached to the positive terminal. When the power is turned on, electrons are pumped into the steel object, making it the cathode of the cell. As long as the steel object is receiving electrons, it cannot be oxidized. Impressed current is often used for structures that are too large to make the use of the sacrificial anode economically feasible. For example, many of Canada's oil and natural gas pipelines are protected using impressed current.

impressed current a form of cathodic protection in which electrons from a DC power source are pumped into the metal that is being protected

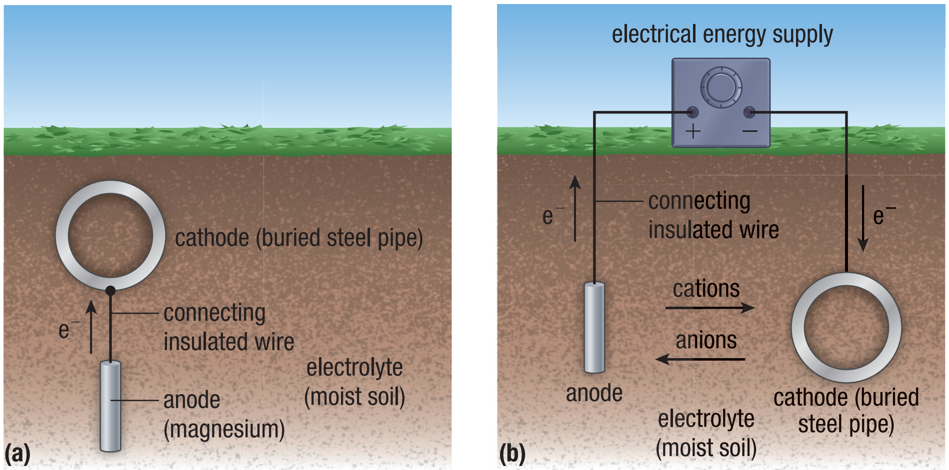

Figure 8 Two methods of cathodic protection that can be used to reduce the corrosion of a buried pipeline by supplying electrons: (a) attaching a sacrificial anode and (b) impressing a current

Research This

Corrosion and Health

Skills: Researching, Defining the Issue, Identifying Alternatives, Defending a Decision

SKILLS HANDBOOK A5.1

Prior to 1960, builders frequently used lead in home construction and decoration. At the time, it was considered a safe and practical material, with many useful applications. Lead has since been linked to several health problems. Many owners of older homes would like to remove the source(s) of lead contamination. In practice, however, this may not always be a viable or economical option.

1. Research sources of lead contamination in older homes.
2. Research the health risks associated with exposure to lead.

A. What are the most likely places where lead may be encountered in a home? K/U

B. How does lead from these places enter the human body? K/U

C. What effects can lead have on a person? Are certain segments of the population more vulnerable to the negative effects of lead? Explain. K/U

D. Why is lead removal sometimes impractical? K/U A

E. Other than removing the lead altogether, what other treatments or processes can be used to reduce human exposure to lead in an older home? K/U A

F. Given that lead was once thought to be safe and is now known to cause health problems, what steps would you recommend to ensure the safety of the materials used in home construction today? Why? K/U A

WEB LINK

10.6 Review

Summary

- Corrosion is the breakdown or deterioration of a metal by a redox reaction.
- Most metals spontaneously corrode when exposed to oxygen and water.
- Dissolved salt allows corrosion to occur faster, but it does not cause corrosion.
- A corroding piece of iron is similar to a galvanic cell. Oxygen is reduced at the cathodic region, and iron is oxidized at the anodic region. Electrons travel through the metal from anode to cathode, while dissolved ions travel through the water to maintain neutrality.
- Corrosion prevention methods include coating with paint or a corrosion-resistant metal layer, such as galvanizing with zinc; using corrosion-resistant alloys; and using cathodic protection (with a sacrificial anode or an impressed current).

Questions

1. Use Table 1 in Appendix B7 to answer the following questions. K/U T/I
   (a) Which metal, zinc or tin, best protects iron against corrosion?
   (b) Why does iron corrode readily in acidic solutions, while gold and silver do not?
2. What substances must be present for iron to corrode? K/U
3. (a) Rank the following metals in terms of their tendency to oxidize, based on your knowledge of the metals and their uses in everyday life: gold, zinc, magnesium, iron.
   (b) Rank the metals in Part (a) using a redox table. Try to account for any differences from your ranking in Part (a). T/I A
4. Why do many Canadians have the underside of their cars sprayed with oil before each winter? T/I A
5. Explain why galvanized steel nails are suitable for exterior use, while regular steel nails are not. T/I A
6. (a) Use a Venn diagram to compare the mechanisms by which sacrificial anodes and impressed current prevent corrosion.
   (b) What do you think is a significant limitation for the use of impressed current to protect a steel structure from corrosion? K/U C A
7. To investigate the effects of corrosion, steel nails were exposed to different conditions in four test tubes:

   Test tube A: steel nails in water and air

   Test tube B: steel nails in a drying agent

   Test tube C: steel nails in distilled water and oil

   Test tube D: steel nails in salt water

   Figure 9 shows the results of the investigation. Explain why some of the nails had evidence of corrosion, while others did not. T/I

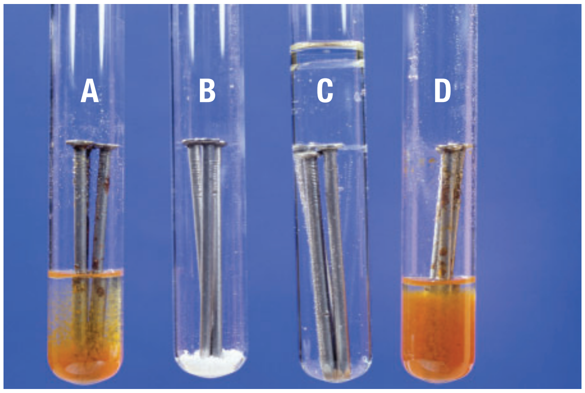

Figure 9 Testing corrosion under different conditions

8. What are rusticles, and how are they formed? Why are they a cause for concern among scientists? Research "rusticles from the sunken hull of the *Titanic*" to find articles that answer these questions. T/I

WEB LINK