

CORROSION in the



CLASSROOM

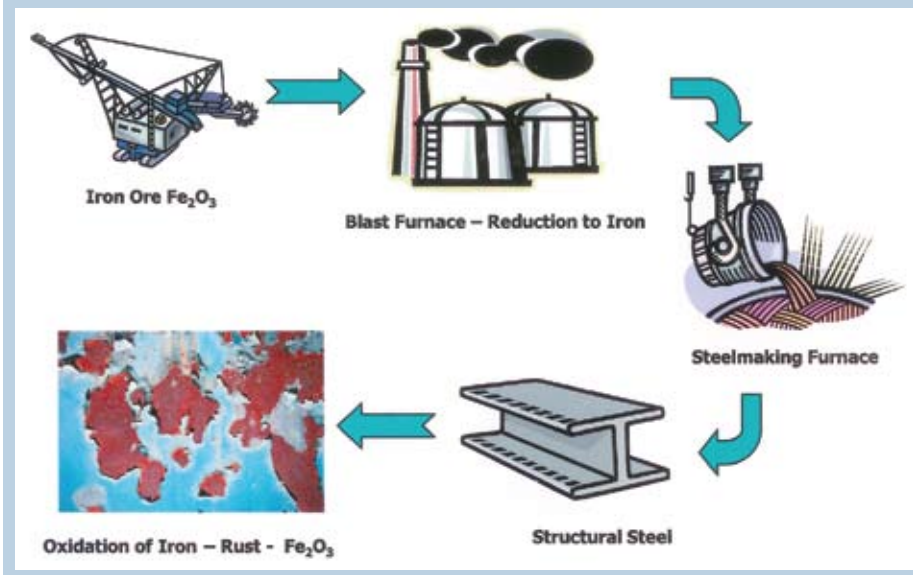
_____ Gary S. Drigel, Arlyne M. Sarquis, _____
and Mike D'Agostino

*Two hands-on
lab activities help
students understand
the corrosion of steel*

Corrosion happens all around us—our cars rust, bridges and other steel structures fail, and this country spends billions of dollars each year in replacement and maintenance costs as a result (Koch et al. 2002)—but few people take the time to understand its impact on our everyday lives. The analysis and activities described in this article provide high school chemistry and science teachers with hands-on lab experiments designed to make students more aware of corrosion and the processes used to prevent or control it (D'Agostino 2005). These experiments will also provide opportunities for high school students to gain relevant, authentic practice with workplace readiness skills and to learn about potential career paths in chemistry and engineering.

FIGURE 1

Corrosion of steel life cycle.



ers, ships, and cars—where they are exposed to both oxygen and water. As a result, steel begins to “rust” or corrode and reverts back to some form of iron oxide, which, again, is iron ore (Yunovich et al. 2000)—shown schematically in Figure 2.

Corrosion in the United States causes about \$276 billion per year in damages (Koch et al. 2002). Types of corrosive attack that cause damage to buildings, bridges, and other steel structures include: general attack (uniform corrosion), pitting/crevice attack (localized corrosion), cracking (embrittlement), and galvanic corrosion (an electrochemical process involving two different metals in which one corrodes preferentially to the other when both come in

Corrosion and steel

Corrosion is the last stage of a steel products’ life cycle (Figure 1). First, iron ore (which is primarily iron oxide) is mined from the Earth. Then, it is reduced to a more pure form of iron using a blast furnace in a smelting operation. Next, the liquid iron is further refined in an oxidation process called *steelmaking*. In the steelmaking process, alloying elements (primarily carbon) are added to produce steel. Steel is then further processed into usable shapes by rolling, forging, and casting. The resulting steel products are put into service—for example, as skyscrap-

contact with a liquid electrolyte.

There are a number of methods used to minimize or prevent corrosion, which include alloying, metallic coating, organic coating, use of inhibitors, and anodic or cathodic protection. Corrosion inhibitors are chemicals that, when added in small concentrations, stop or slow down corrosion. Anodic/cathodic protection involves electrochemical corrosion control techniques that allow an attached, more active “sacrificial” metal to be preferentially oxidized, thus protecting the metallic structural component from corrosion. Through the following lab activities, students explore the processes of corrosion and the means to control it.

FIGURE 2

Corrosion in action.

A painted steel structure has begun to fail as a result of corrosion.



Lab activity 1: Corrosion process experiment

Unprotected steel will corrode when exposed simultaneously to oxygen and water, or air and rain. To prevent corrosion, steel can be coated with a number of substances to create a barrier between the metal and the corrosive environment. In this activity, students investigate the effectiveness of various nonmetallic coatings in preventing or inhibiting corrosion. In the real world, the coatings would most likely be paints or metals. However, testing the effectiveness of either of these coatings within the timeframe and budget of a typical chemistry course is not practical. Therefore, the activity tests coatings that are somewhat less effective at preventing corrosion but are much more familiar and available to students.

In this exercise, students subject one unprotected and two protected iron strips to a corrosive environment within an agar petri dish. One protected iron strip is wrapped with copper wire, the other with zinc; the unprotected iron strip remains as it is. The protected iron strips are then placed in a petri dish together, though they should not touch each

FIGURE 3

Lab activity 1: Materials and instructions.

Materials

- ◆ 2 petri dishes with covers
- ◆ 1.5 g powdered agar (not nutrient agar)
- ◆ 100 mL 0.1 M sodium nitrate
- ◆ distilled/deionized water
- ◆ 250 mL beaker
- ◆ white background paper
- ◆ black background paper
- ◆ beaker tongs
- ◆ burner/hot plate
- ◆ glass stir rod
- ◆ 0.1 M potassium ferricyanide in a small dropper bottle
- ◆ 100 mL phenolphthalein indicator in a small dropper bottle
- ◆ 10 cm length of copper wire
- ◆ 10 cm length of zinc wire or thin zinc strip
- ◆ steel wool
- ◆ three 6 cm x 1 cm iron strips

Lab instructions (Masterson and Hurley 1989)

1. Heat 100 mL of 0.1 M sodium nitrate to boil in a 250 mL beaker. While stirring with a glass rod, add 1.5 g of powdered agar. Heat and stir the mixture until agar forms a suspension.
2. Add 10 drops of 0.1 M potassium ferricyanide and 10 drops of phenolphthalein indicator to the agar suspension. Stir to mix thoroughly.
3. Clean three 6 cm x 1 cm iron strips with steel wool.
4. Place one 6 cm x 1 cm iron strip in the bottom of the first petri dish.
5. Polish the 10 cm copper wire and the 10 cm zinc wire with steel wool.
6. Lightly wrap the 10 cm copper wire around the second 6 cm x 1 cm iron strip.
7. Lightly wrap the 10 cm zinc wire around the third 6 cm x 1 cm iron strip.
8. Place the second and third wrapped iron strips in the bottom of the second petri dish. Do not allow the two wrapped strips to touch each other.
9. Pour enough warm agar in both petri dishes to cover all of the iron strips to a depth of about 1 mm.
10. Cover both dishes and let stand for about 24 hours.
11. On day 2, observe the petri dishes against both white and black backgrounds and record your results.

Safety instructions for teachers

- ◆ Collect and read the Materials Safety Data Sheets (MSDS) for all of the chemicals used in experiments.
- ◆ Read and follow the American Chemical Society Minimum Safety Guidelines for Chemical Demonstrations.
- ◆ Review each activity carefully and observe all safety precautions and disposal procedures.
- ◆ Never attempt an activity if unfamiliar or uncomfortable with the procedures or materials involved.
- ◆ Always practice activities before using them with the class.
- ◆ Wear safety goggles and gloves when participating in the preparation for or doing of the activity—applies to teachers, assistants, and students.
- ◆ Use common sense when working with hot, sharp, or breakable objects.

other; the unprotected iron strip is placed in its own petri dish. Indicators, which are added to the agar solution before the iron strips are placed, allow students (after a 24-hour period) to witness corrosion and the protective process of galvanization, in which surfaces of iron or steel products are coated with a thin layer of zinc to prevent corrosion.

The experiment is followed by guided questions and an instructor-guided discussion. Instructor questions could include:

- ◆ Why does the iron behave differently in the three cases observed in this experiment?
- ◆ Can you think of any other uses for the processes you observed in this experiment?
- ◆ Have you heard about the bridge that collapsed in Minneapolis, Minnesota? Do you think that

corrosion may have played a role in this collapse (NTSB 2007)?

See Figure 3 for materials needed, lab procedures, and safety instructions.

Typical observations

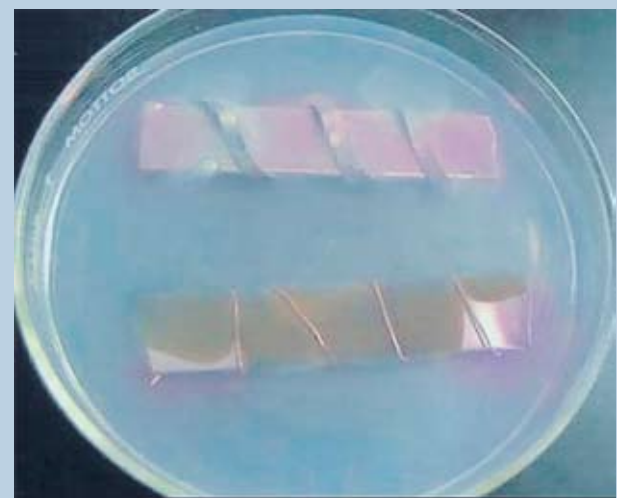
Through this lab activity, students explore the rusting process in an agar medium. In the petri dish containing the unprotected iron strip, corrosion of the iron should occur and the cathode and anode regions should be clearly seen (Figure 4). The anode is the negative part of a cell (galvanic) *to* which current flows. A cathode is the positive part of a cell (galvanic) *from* which current flows.

FIGURE 4**Lab activity 1: Dish 1, day 2.**

Unprotected iron in agar containing potassium ferricyanide and phenolphthalein.

**FIGURE 5****Lab activity 1: Dish 2, day 2.**

Wrapped iron strips in agar containing potassium ferricyanide and phenolphthalein. (Shows zinc cathodic protection of iron [top] and iron cathodic protection of copper [bottom].)



In this activity, the cathode is the region where the phenolphthalein indicator, an indicator that turns colorless in acidic solutions and pink in basic solutions, within the agar has turned pink. The formation of the intermediate hydroxide ion, produced from the oxygen in the water, is seen prior to its migration to the anode by the color change of the indicator to pink. The anodic region—in which the agar should be slightly darker—is where the rust has formed. This dark color arises from the formation of iron (II) ions and the positive test of the potassium ferricyanide indicator, which produces a red color.

In the petri dish containing the two protected iron

strips, corrosion should occur in one case (Figure 5). The iron strip wrapped with copper wire should have corrosion very similar to the unprotected iron strip described above. Copper is a less active metal than iron, and therefore provides no galvanic protection. Unlike copper, zinc is a more active metal and is therefore more likely to provide the electrons that iron was providing in the previous case. Thus, the zinc-wrapped iron strip is not corroded. This process is characteristically known as *galvanization*, or cathodic protection.

In the case of the zinc-wrapped iron strip, the zinc is the sacrificial anode—in other words, iron is no longer the anode, although it still gives up electrons to the system. But because zinc is more easily oxidized than iron, the zinc immediately transfers electrons to the iron ions, reducing them back to neutral iron atoms. No darkening of the agar occurs in this petri dish because no iron (II) is present. However, a white precipitate, zinc hydroxide, should form around the zinc strips, which is a preferred species as compared to iron (II) hydroxide because it is similar in color to zinc and is therefore more aesthetically pleasing to the eye than the red-orange colored rust (iron [II] hydroxide). More importantly, the iron wrapped with the zinc strip has “escaped” corrosion. See Figure 6 (p. 54) for more typical observations.

Assessment

For assessment purposes, students can compile the information and observation data into tables and write a paragraph summarizing their conclusions. Directions for the paragraph can be written as follows: “Discuss the observations in the Petri dishes, including conclusions that can be drawn from the colors of the indicators and precipitates. Explain how cathodic protection works.”

For this assignment, students should be expected to note the color differences. Any explanation of why copper did not stop corrosion but zinc did is a more advanced analysis. Further, an explanation of cathodic protection demonstrates an even deeper level of understanding. The most advanced students might hypothesize examples of other applications for this process.

Lab activity 2: Building Bridges project

Corrosion of bridge structures is the primary reason for bridge collapse or failure and bridge replacement (Yunovich et al. 2008). Therefore, when constructing a new bridge, a team of professionals must decide on the most appropriate materials for minimizing or preventing corrosion of the bridge while working within a realistic budget.

In the Building Bridges activity, students assume the role of a team of professionals specializing in corrosion prevention. By using previously learned concepts or their own research and selecting the materials (rebar and coating) to be used in the construction of three new bridges,

FIGURE 6

Lab activity 1: Typical student observations.

Time	Item	Experimental conditions	Observations	Sketch
Day 1	Dish 1	Iron in agar + phenolphthalein + potassium ferricyanide	Unprotected iron: Light pink cloud starts to form around iron. The iron surface itself appears darker blue.	Unprotected iron
	Dish 2 zinc	Iron wrapped with zinc in agar + phenolphthalein + potassium ferricyanide	Wrapped iron: Light pink cloud starts to form. No darker blue on iron.	Wrapped iron
	Dish 2 copper	Iron wrapped with copper in agar + phenolphthalein + potassium ferricyanide	Wrapped iron: Light pink cloud starts to form. Slightly darker blue color appears on iron surface.	Wrapped iron
Day 2	Dish 1	Iron in agar + phenolphthalein + potassium ferricyanide	Unprotected iron: A larger, darker pink cloud surrounds the metal strip. A dark blue color is also forming close to the strip in patches.	Unprotected iron
	Dish 2 zinc	Iron wrapped with zinc in agar + phenolphthalein + potassium ferricyanide	Protected iron: A larger, darker pink cloud is present, and a white solid surrounds the zinc. The iron is still metallic gray.	Protected iron
	Dish 2 copper	Iron wrapped with copper in agar + phenolphthalein + potassium ferricyanide	Protected iron: A darker pink cloud surrounds the iron strip. The iron strip is darker blue in patches.	Protected iron

(WILBRAHAM, STALEY, AND MATTA 2000)

students learn how a designer or engineer uses observations and historical data to specify the requirements for bridges built in different locations. Students will also come to see that the environment has a very significant effect on the choices that are made and that bad choices could lead to the failure and possible collapse of the bridge. See Figure 7 for background information that can be given to students ahead of time and Figure 8 (p. 56) for the complete lab activity.

Conclusion

Corrosion is a scientific process that significantly affects the world around us. On August 1, 2007, the Interstate I 35-W bridge collapse in Minneapolis, Minnesota—that killed 13 and injured 145—thrust bridge failure into the spotlight (Salisbury 2008). While investigators with the National Transportation Safety Board (NTSB) have recently identified a design flaw, not corrosion, as the critical factor responsible for the collapse (Frommer 2008), steel corrosion in bridges has the potential to cause similar catastrophes.

Analysis of the Minnesota bridge collapse is expected to continue until late 2008. Equipped with the basic knowledge of corrosion provided by the activities in this article, teachers and students are encouraged to follow the investigation, corrective actions taken as a result of this bridge collapse, and construction of the replacement

bridge through the state of Minnesota and NTSB’s websites (see “On the web”). Through the understanding and awareness gained through the activities in this article, students may help to prevent future catastrophes involving our nation’s steel infrastructure. ■

Gary S. Drigel (drigelgs@muohio.edu) is an assistant professor of mechanical engineering technology and Arlyne M. Sarquis (sarquiam@muohio.edu) is the director of the Center for Chemistry Education, both at Miami University in Middletown, Ohio; Mike D’Agostino (dagostino.ma@pg.com) is a scientist at Procter and Gamble in Cincinnati, Ohio.

Acknowledgments

The information provided in this article is adapted from *Corrosion of Steel Structures*, a text book/lab manual developed as part of a National Science Foundation grant to Miami University (Ohio) entitled “Using Chemistry to Enhance the Technical Workforce in the Innovation Age.” These activities and many others are available online from the Center for Chemistry Education (CCE) at Miami University (Ohio) (see “On the web”).

On the web

State of Minnesota: www.dot.state.mn.us/
 National Transportation Safety Board (NTSB): www.nts.gov
 Center for Chemistry Education (CCE) at Miami University (Ohio): www.terrificscience.org.

FIGURE 7

Lab activity 2: Reading assignment.**Construction of steel-reinforced concrete bridge decks**

Steel-reinforced concrete bridges are among the most common type of bridge built. In fact, the vast majority of highway bridges are of this type and are most frequently encountered along interstate highways. For added strength and support, the concrete used in constructing these bridges is often reinforced with imbedded steel bars, commonly called *rebar*.

The basics of rebar

Steel-reinforced concrete bridge decks, the roadway surfaces of a bridge, are composed of concrete that has been reinforced with imbedded steel bars. These bars, called *rebar*, are typically round and vary in diameter. When a bridge deck is built, the rebar structure is commonly built and supported in place first, and then concreted is poured over, around, and through the bars. Why is the rebar needed? Concrete alone is a very hard and somewhat brittle material. It performs very well under compression loads but tends to be very weak under tension loads. Tension is an axial load that pulls a section apart. Compression is an axial load that pushes a section together. The rebar is added to the concrete to increase the tensile strength of the bridge deck.

There are typically five different types of rebar used in the construction of reinforced concrete bridges. These include: as-rolled rebar (mill scale), epoxy-coated rebar, stainless steel rebar, stainless steel clad rebar, and galvanized (zinc) rebar. The Building Bridges activity will provide more information about each type of rebar. Like other metals, rebar has the potential to corrode. Addition of inhibitors, such as calcium nitrate or silica fume, can slow the rate of corrosion in the rebar and thus, improve the structural integrity of the bridge deck (Chase and Washer 1997).

Corrosion of the rebar

The quality of the bridge deck is only as good as the bond between the rebar and the concrete. When the rebar in the deck begins to

corrode, the integrity of the bond between the rebar and concrete is significantly affected. This can lead to large decreases in strength and eventual failure of the bridge. Much of the corrosion that occurs is induced by the presence of chloride, most commonly found in salts (Johansen, Klemm, and Taylor 2002). The chloride can come from many sources, including road salt, rainwater runoff, and the air. In the case of a Florida bridge in the Building Bridges activity, the sand used to make the concrete roadbeds originally came from nearby beaches. In this concrete, the chloride ion was present from the time the bridge was constructed and had been causing corrosion from the very beginning, eventually leading to its catastrophic failure.

Monitoring corrosion of the rebar

The government monitors the chloride ion concentration within concrete samples as a measure of the amount of corrosion that is occurring. Unfortunately, one cannot examine the rebar directly without destroying the concrete bridge deck. Therefore, indirect techniques must be used to determine the “state” of the rebar within the concrete. These indirect techniques include x-ray, conductivity, and chloride ion concentration tests. Chloride is a proxy for corrosion: the more chloride detected in a sample of concrete, the more corrosion that is probably underway.

Traditionally, the Federal Highway Administration takes samples from concrete bridges and sends them to a laboratory for analysis using a procedure called *potentiometric titration*, a complex and time-consuming laboratory procedure that analyzes acid-soluble chloride in cement using an electronic device. New Mexico State Highway and Transportation measures concentration using a chloride-specific ion probe. Although not as accurate as the laboratory tests, the results are perfectly sufficient for an estimate of the chloride ion concentration, and thus the degree of corrosion in the concrete.

References

- Chase, S.B., and G. Washer. 1997. *Nondestructive evaluation of bridge management in the next century*. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.
- D’Agostino, M. 2005. Integrating corrosion testing industrial protocols into a high school/two-year college chemistry curriculum. Master’s thesis, Miami University, Ohio.
- Frommer, F. *The Associated Press*. 2008. Government: Design Flaw in Bridge Collapse. January 15.
- Johansen, V.C., W.A. Klemm, and P.C. Taylor. 2002. *Why chemistry matters in concrete*. Skokie, IL: Concrete International.
- Koch, G.H., M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Payer. 2002. *Corrosion costs and prevention strategies in the United States*. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.
- National Transportation and Safety Board (NTSB). 2007. Second Update on NTSB’s Investigation of the Collapse of the I-35W Bridge in Minneapolis. August 22.
- Salisbury, B. *Pioneer Press*. 2008. I-35W Bridge Collapse/Oberstar Criticizes NTSB Chairman. January 23.
- Svirsky, A. 2008. National Bridge Inventory Database. <http://nationalbridges.com>
- The Weather Channel Inc. 2008. Monthly averages. www.weather.com/weather/wxclimatology/monthly/graph/USAZ0247?from=search
- Wilbraham, A., D. Staley, and M. Matta. 2000. *#45 Corrosion lab manual, teacher’s edition*. Upper Saddle River, NJ: Prentice-Hall.
- Yunovich, M., N.G. Thompson, T.B. Balvanos, and L. Lave. 2000. *Corrosion costs and preventive strategies in the United States, appendix D—Highway bridges*. Dublin, OH: CC Technologies.
- Yunovich, M., N.G. Thompson, T.B. Vanyos, and L. Lave. 2008. Cost of corrosion. www.costofcorrosion.com/infrastructure/highway/index.htm

FIGURE 8**Lab activity 2: Building Bridges project.****The problem**

The National Bridge Inventory Database shows that there are about 600,000 bridges in the United States (Svirsky 2008). Most of these bridges were built before 1994 and maintenance of these aging bridges is a significant cost—oftentimes higher than the cost to construct the bridges themselves. The annual direct cost of corrosion for highway bridges is estimated to be about \$8 billion (Yunovich et al. 2000). Because of these high maintenance costs, the government carefully scrutinizes the design, construction, and corrosion prevention of new bridges, including three slated to be constructed in Florida, Minnesota, and Arizona.

Your task

In this activity, you will assume the role of scientist, engineer, construction worker, and so on, specializing in corrosion prevention. Using concepts learned from previous lab activities along with the supplemental data and information provided or your own research, you will decide upon the materials (rebar and coating) to be used in the construction of these three new bridges. As you select the materials, you will need to consider the rust-protecting ability, lifetime, and cost of the materials, along with the environment in which the bridge is being built.

Procedure

1. Table 1 below contains important information about the locations where each of the new bridges will be built. Review this information, considering how these details may influence the types of materials necessary for construction of a bridge in the area.

Table 1: Environmental information concerning the location of future bridges.

(Note: Values based on yearly high and low temperatures for example cities [The Weather Channel Inc. 2008].)

	Bridge #1*	Bridge #2	Bridge #3
Location	Key Largo, Florida	Duluth, Minnesota	Tucson, Arizona
Average temperature ranges	11°–36°C	-36°–27°C	4°–47°C
Humidity	High (60–100%)	High (60–100%)	Very low (~20%)
Winter conditions	No snow or freezing temperatures	Highest snowfall of any U.S. city	No snow or freezing temperatures
Required lifespan	40 years	70 years	100+ years

* Processed (salt free) sand will be used to mix the concrete.

2. Review the information in Table 2 below, which provides information about the possible types of corrosion-control rebar available for construction of the new bridges.

Table 2: Summary of costs and life expectancy for steel-reinforced concrete.

Type of rebar/inhibitor	Cost of bar (\$/kg)	Cost per deck area (\$/m ²)	Increase in cost compared to as-rolled rebar (\$/m ²)	Estimated service life (years)
As-rolled	\$0.44	\$11.60	Baseline—0	10
Epoxy-coated	\$0.66	\$17.40	\$5.80	40
Solid stainless steel	\$3.85	\$101.64	\$90.04	75–120
Stainless steel clad	\$1.54	\$40.66	\$29.00	50
Galvanized	\$1.00	\$26.40	\$14.80	40
Calcium nitrate inhibitor	N/A	N/A	\$5.40	30
Silica fume inhibitor	N/A	N/A	\$4.30	20

3. Using the information from Tables 1 and 2, along with your previous knowledge, determine what type of rebar and coating should be used in the construction of each of the three bridges. Be sure to consider the cost-effectiveness of the materials and what you already know about environmental effects on corrosion.

Assessment

Write a three paragraph statement to your supervisor summarizing your choice of building materials for each bridge (one paragraph per bridge). Be sure to include the reasons for your choices. Your statement should convince your supervisor that each bridge will be safe, rust-protected, and economically reasonable given its location.