Part II

CORROSION:

What's Eating at Your Metal?

By Cris Crissinger, CCS, CCCA, ASQ

This article has been published in two parts. Part I appeared in the July 2013 edition of* Interface *and discussed basic corrosion principles and galvanic reaction. Part II explains why some metals are more corrosion-resistant and their reactions in cementitious materials.

CORROSION-RESISTANT METALS

Stainless Steel

Even though stainless steel is positioned at the "noble" end of the Galvanic Series Tables, it does not occur naturally. The occasional references to it as being a noble metal are incorrect as determined by the previously discussed definition of a noble metal (see July 2013 *Interface*). There is a misconception that all stainless steel is alike and is corrosion-resistant. Stainless steel is an excellent metal and should not get a bad reputation because of poor application. Just as the term "wood" is used to embrace a wide range of species, with each species having different properties, there are different alloys of stainless steel and each alloy has its own properties. When the species of a particular wood is not known, that wood is sometimes referred to as "tree wood." Similarly, stainless steel is often specified as "stainless steel" with no mention of alloy.

Just as some roofs perform better than others under specific conditions, the same can be said for stainless steel. This is because some stainless-steel alloys are more corrosion-resistant than others. Therefore, the stainless-steel type, as determined by its alloy, must be matched to its environment. I recall that while living in Charleston, South Carolina, a friend (believing that stainless steel was low-maintenance and rust-proof) purchased one of the new stainless-steel revolvers to keep in the cabin of a fishing boat. There was considerable shock when, over time, some of the shiny silver-looking metal had small pits and turned a cinnamon color. The lesson learned is that not all stainless steel is rust-proof.

The American Iron and Steel Institute (AISI) lists over 50 types of stainless steel. These types are usually identified by 200, 300, or 400 series numbers, with Types 301, 304, 316, and 410 being those most frequently associated with design and construction.

- Austenitic: Types 200 and 300 Series (304, 316) are nonmagnetic and have reasonably good corrosion resistance. Type 304 (18% chromium, 8% nickel) is the general-purpose alloy in this group and is often referred to as 18-8 stainless steel.
- Martensitic: 400 Series, such as Type 410, is the general-purpose alloy of this group. It is very magnetic and is corrosion-resistant in mild atmospheres.
- Ferritic: 400 Series, such as 430, is magnetic and has good corrosion resistance.

Just as all stainless steels do not have the same corrosion-resistant properties, they do not have the same fabrication properties such as welding, bending, hardening, etc. Therefore, when considering fabrication and application of stainless steel, design professionals should consult publications by the International Molybdenum Association (IMOA) or Specialty Steel Industry of North America.

Aluminum

Aluminum is not actually a corrosion-resistant metal. Even though aluminum's position on the Galvanic Series Table indicates a reactive metal, more accurately, under most conditions, aluminum's corrosion rate is just extremely slow or is in a static state. Aluminum is very active and tends to oxidize quickly to form a white, chalky passivating film as shown in *Photo 6*. Actually, very few metals are more reactive than aluminum, and those metals are not normally used in building construction. Beryllium, potassium, sodium, and magnesium are examples. This rapid oxidation is a benefit instead of a detriment, because the aluminum oxide film forms a strong bond to the aluminum surface and seals the aluminum from oxygen. For this reason,

Photo 6 – Aluminum oxide on a coastal ladder. (Photo by Cris Crissinger.)

it offers excellent resistance to corrosion and provides years of maintenance-free service in natural atmospheres. This is the opposite of common steel corrosion, where the oxidized metal (rust) flakes off and exposes more metal to corrosion.

According to the Aluminum Association, the galvanic process is a very common cause of aluminum corrosion. As long as the aluminum oxide remains intact, no further corrosion will occur. Because of its inherent resistance to other forms of corrosion, when aluminum comes into contact with less reactive metals, aluminum acts as a sacrificial anode and becomes susceptible to corrosion.

At an ambient temperature of 80°F, the normal surface film formation ranges from approximately 2 to 50 nanometers thick. If that protective layer is scratched or abraded, a protective film re-forms immediately in most environments and ensures continued protection. Consequently, aluminum and its alloys can be used in a wide range of building applications that include flashings, copings, gutters, downspouts, roof panels, window frames, stairs, ladders, fences, railings, pipe, and many more applications other than construction.

Although aluminum has a huge advantage compared to other metals regarding corrosion, it is not always completely immune to corrosive reactions. Its protective oxide layer can become unstable when exposed to extreme pH levels. A highly acidic or alkaline environment can break down the protective layer and make the aluminum more susceptible to corrosion. According to the U.S. Army Corps of Engineers, aluminum's protective oxide film is generally stable in the pH range of 4.5 to 8.5.

Aluminum corrosion is not normally noticed in freshwater lakes, pools, etc., but it can become more obvious in or near the ocean. It may seem logical to conclude that the saltwater, because of its alkalinity, is corrosive to the aluminum. In reality, saltwater does not corrode aluminum because of its neutral pH. However, saltwater can become the electrolyte for galvanic corrosion.

Just as various stainless steel alloys have different strengths and corrosion-resistant properties, so do aluminum alloys. When corrosion resistance and strength are design factors, marine-grade aluminum

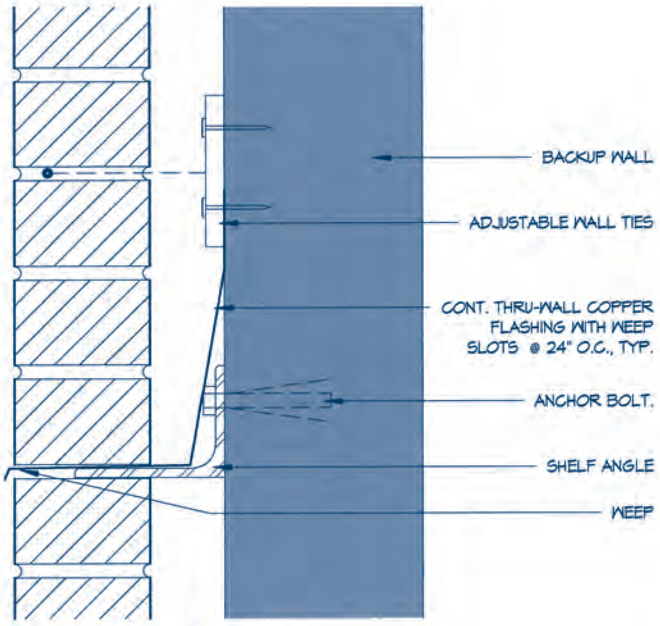

Figure 3 – Common detail. (By Homer Nestlen of McMillan Pazdan Smith.)

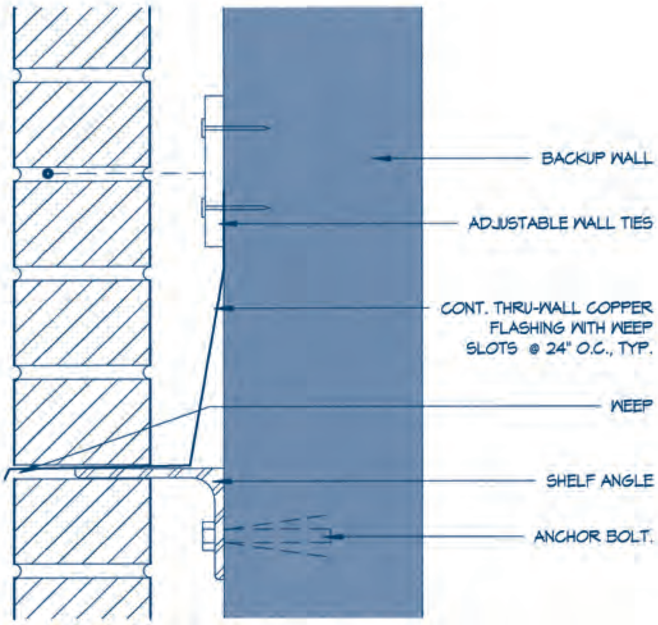

Figure 4 – Recommended detail. (By Homer Nestlen of McMillan Pazdan Smith.)

Photo 7 – Mortar expelled by expanded and corroded reinforcement. (Photo by Cris Crissinger.)

Photo 8 – Exposed masonry reinforcement. (Photo by Cris Crissinger.)

alloy such as 6061 or 6063 should be considered, according to the Aluminum Association. However, 7075 alloy has a significantly higher strength than 6061 or 6063 but has inferior corrosion resistance.

Atmospheric Corrosion of Copper

Since copper is a noble metal and is generally stable in most atmospheric conditions, it is often used for gutters, downspouts, roof panels, and trim for historic structures and is highly recommended for through-wall flashing and other applications where it will come into contact with moisture.

Proper detailing of copper through-wall flashing can prevent galvanic action. *Figure 3* is a common method of showing the leg of a shelf angle turned up and the flashing carried over the anchor bolt. If the flashing is metallic, such as copper, a potential galvanic cell is created between the steel bolt (anode) and the copper (cathode). *Figure 4* shows the leg turned down, preventing contact with the flashing. Since the steel angle (anode) is significantly larger than the copper (cathode), the larger anode-to-cathode ratio reduces the corrosion potential of the steel.

As copper corrodes, it develops a strong self-adhering oxide layer similar to the reaction of aluminum. Like aluminum, as the corrosion process advances, the layer thickens and forms the familiar green patina often associated with copper roofs. Sulfur dioxide that forms in the atmosphere from burning fossil fuels can hasten the transition from oxide layer to patina. In applications such as roofing, where the green patina has aesthetic value, the increase in formation of patina is desirable.

Since copper is highly noble, it is frequently used for most atmospheric applications such as sheet metal work for roof and wall flashing, gutters, downspouts, trim—and, sometimes—roof panels. However, copper should be avoided in locations with elevated levels of sulfur or ammonia. If copper must be used in these environments, it can be treated with nickel-plating or tin-plating, which act as oxide inhibitors.

STEEL CORROSION AND CEMENTITIOUS CONSTRUCTION

Water from various sources and oxygen from the air take many paths to the interior of the concrete or concrete masonry units to consume underprotected steel. The iron oxide formed by the corrosion usually bonds to the steel, loosely causing the original volume of the steel to increase many times. The loosely bonded corrosion falls off, exposing more metal that will also corrode and fall off. This cycle continues, causing the metal to eventually disintegrate completely. The volume increase created by the corrosion can push mortar out masonry joints and will eventually force the horizontal reinforcement from the joints. Similarly, corroding steel rebar can cause concrete to spall. *Photo 7* shows mortar being pushed from a masonry joint by corroding reinforcement, *Photo 8* shows exposed reinforcement, and *Photo 9* shows corroded masonry anchors. In addition to steel corrosion,

Photo 9 – Corroded masonry ties. (Photo by Cris Crissinger.)

Photo 10 – Spalled concrete caused by expanded corroded rebar. (Photo by Bailey and Son Engineering.)

efflorescence is a very visible sign of saline activity in cementitious construction. *Photo 10* shows spalled concrete and corroded rebar in a fertilizer plant. Excluding using protective coatings such as galvanizing or epoxy, corrosion of reinforcement in cementitious construction can be controlled by:

1. Not using ocean sand in mixes
2. Using integral water-repellent in mortar
3. Not using admixtures that contain chlorides
4. Using concrete with a low water-to-cement ratio
5. Tooling masonry joints to create a smooth mortar matrix
6. Using dense concrete with smooth finish and thick cover over the rebar
7. Not pressure-washing masonry, which can destroy the water-resistant mortar matrix
8. Using concrete and mortar materials and mixes with minimum proportions of alkali and sulfates

Since an electrolyte is a necessary component of corrosion and water can be an electrolyte, corrosion tends to occur where rainwater or condensation cannot run off or evaporate quickly. Porous masonry can act like a giant sponge and absorb moisture from the atmosphere. Since heat tends to invigorate corrosion, when the sun warms the walls, the moisture also warms and begins to move as a vapor and increases the corrosion potential.

ZINC, GALVANIZING, GALVALUME®, AND ANODIZED ALUMINUM

Zinc

Zinc is a fairly reactive metal and is used in sheet-metal work, but is probably best known for its use in galvanizing. Like aluminum, it forms a white-powder protective coat (an oxide), sometimes referred to as white rust, when exposed to the elements. For instance, oxygen from the atmosphere causes zinc to quickly change to zinc hydroxide; and carbon dioxide—also in the atmosphere—changes the zinc hydroxide to zinc carbonate, which stops the reaction and prevents further corrosion.

Galvanizing

Galvanizing is a simple example of cathodic protection consisting of a protective coating of zinc and ferrous metal such as steel that are bonded together with no electrolyte. As long as the zinc coating is not breached, there is no reaction. When galvanizing is exposed to corrosion, it forms zinc's characteristic white rust as shown in *Photo 11*, where the exposed steel edge is beginning to corrode and the galvanizing is sacrificing itself. If the zinc film is broken to expose the ferrous metal, the zinc will begin to sacrifice itself to prevent corrosion of the steel metal. The zinc coating is usually applied by one of the following two methods:

- **Hot-Dipped Process:** Dipping the base (ferrous) metal in a vat of molten zinc, providing a thick, dull, gray coat of zinc, usually with the characteristic spangle. This is the most common method of galvanizing and provides the best protection

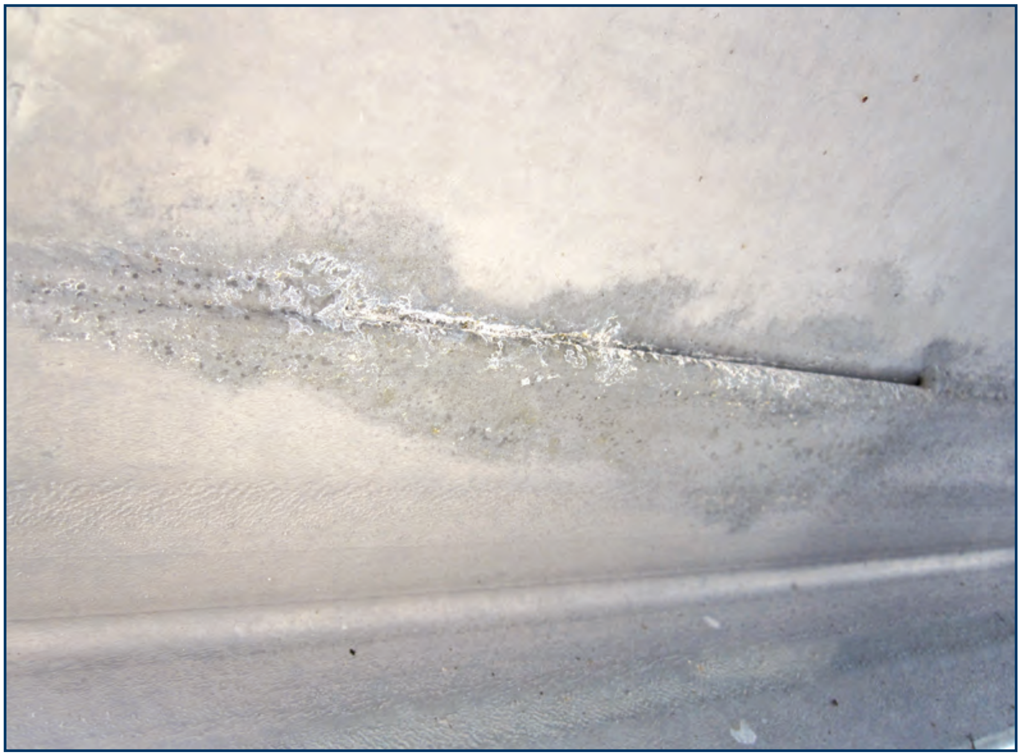

Photo 11 – Corrosion (white rust) on galvanized steel edge. (Photo by Cris Crissinger.)

because its coating is much thicker. Depending on the alloy of the ferrous metal being galvanized, the process may weaken the base metal somewhat. Also, being a thicker coating, hot-dipped galvanizing can fill the threads of bolts—especially those of smaller diameters—thereby reducing holding power of the connection.

- **Electroplating:** Producing a thin, shiny application of zinc coating, sometimes resembling satin stainless steel. Being a thin coat, the plating tends to deplete itself faster than hot-dipped zinc coating. Therefore, it is not usually recommended for exterior or wet applications unless painted or used in an arid climate. However, because of its relatively lower cost, it is frequently used in lieu of hot-dipped galvanizing. This type of plating is used for metal studs and is common for nails used in nail guns.

Corrosion resistance is directly proportional to coating thickness. The two most popular coating thicknesses for galvanized steel are designated G-60 and G-90. The G designates hot-dipped galvanizing, and the number designates the total amount of zinc contained on each side of the sheet. G-60 contains 0.60 ounces of zinc per sq. ft., and G-90 contains 0.90 ounces of zinc. G-180 is often recommended for substrates in contact with treated lumber and has 1.80 oz. of zinc per sq. ft.

Fabricators usually coat the surfaces of zinc and its relatives, galvanizing and Galvalume®, with an oil to prevent the white crust from forming. These oils can be a slip hazard on a galvanized roof deck and must be removed from any surface to be painted. In lieu of oil, fabricators may treat galvanizing with a passivator, which also must be removed prior to applying a protective coating. The oil is easily detected by feel, but a passivator is not usually easily detected. A passivator can be detected by applying copper sulfate to the galvanizing. If the applied area turns black, there is no passivator because of the chemical reaction between the copper sulfate and bare zinc. If there is no color change at the applied area, there is a passivator because the passivator prevented a reaction. (Copper sulfate is usually available from drug stores that still compound prescriptions.)

	Oz./Sq. In. Both Sides	Total Mil Both Sides	Mils Each Side
AZ50	0.50	1.60	0.8
AZ55	0.55	1.76	0.88
AZ60	0.60	1.92	.96

Table 4

Additionally, hot-dipped galvanizing can be touched up with cold galvanizing coatings that have 90-95% zinc in the dry film or zinc-rich epoxy primers that have a zinc content of 80-85% zinc by weight. The cold galvanizing coatings tend to work best because they produce a dry film that has a higher zinc content, which means better sacrificial properties.

Galvalume®

Galvalume® is a trade name that identifies cold-rolled steel sheet that has been coated with an aluminum-zinc alloy. The alloy consists of approximately 55% aluminum, 43.4% zinc, and 1.6% silicon by weight. However, aluminum makes up approximately 80% of the alloy by volume. The coating is applied by dipping the cold-rolled steel sheet into the molten alloy, producing sheet steel having the protective properties of aluminum and zinc and the barrier protection and longevity of aluminum. The zinc also provides better corrosion resistance at the cut or sheared edges.

The two most popular coating thicknesses for Galvalume® are designated as AZ50 and AZ55; however, AZ60 is sometimes used. The AZ stands for aluminum zinc, and the number represents the total combined thickness of coating on both sides of the sheet. An AZ50 has a combined coating thickness of 0.50 oz./sq. in. on both sides, which is equivalent to approximately 1.6 mils. *Table 4* correlates the thicknesses. Both AZ-55 and AZ-50 coatings contain 55% aluminum, 43.4% zinc alloy, and 1.6% silicon. The silicon minimizes the growth of brittle intermetallic layers that form when the product is being coated and allows the alloy to be applied by the hot-dipped process.

Galvalume's® appearance is similar to hot-dipped galvanizing but tends to be smoother and shinier, with a smaller and tighter grain; and its slight spangle is not so prominent as that of hot-dipped galvanizing. These properties tend to produce a smoother finish when they are coated. Performance of hot-dipped galva-

Photo 12 – Passivation (brown rust) on old rifle barrel. (Photo by Cris Crissinger.)

nizing and Galvalume® tend to be similar during the first ten years of service, with perhaps a slight edge to galvanizing. However, Galvalume® begins to outperform hot-dipped galvanizing after approximately ten years and continues to do so for 15 to 20 years or more.

Galvalume® should not be used on, in, or around cementitious materials such as concrete plaster, concrete masonry units, or mortar, because the high alkalinity can react with the aluminum and cause accelerated corrosion. Hot-dipped galvanizing performs better when exposed to cementitious conditions. However, hot-dipped galvanizing is not recommended for and does not perform well as a through-wall flashing, because building movement can cause contact surfaces to abrade the galvanizing and expose the ferrous substrate.

Both coated and uncoated Galvalume® can deteriorate quickly when exposed to animal excrement, so they should not be used in or around areas that house livestock. However, coated and uncoated Galvalume® can be successfully used in marine and most industrial environments.

Anodized Aluminum

Anodizing is a common process that increases aluminum's corrosion and abrasion resistance and provides a chemically bonded color to the aluminum, but it is not the same as galvanizing, which is considered to be a coating. Since aluminum forms a natural layer of protective oxide that prevents or slows the rate of corrosion, anodizing artificially thickens that natural oxide layer—often many times thicker than what would form naturally. This increased thickness provides additional protection. Unlike Galvalume® and galvanizing, anodizing is available in a small range of colors—all having similar performance.

Photo 13 – Corrosion and rust bloom during construction. (Photo by Cris Crissinger.)

Photo 14 – Structural steel corrosion from protective coating failure. (Photo by Bailey and Son Engineering.)

The American Architectural Metals Association publication *AAMA 607.1* classifies two types of clear anodized aluminum, based on coating thickness, as Class I and Class II. Class I has a coating thickness of 0.018 mm or thicker, and Class II has a coating thickness of 0.010 mm or thicker. *AAMA 608.1* governs color-anodized aluminum.

CARBONATION OF CONCRETE AND STEEL CORROSION

Carbonation is a deterioration of the concrete and can cause surface porosity that can allow atmospheric conditions to reach the steel rebar and start corrosion and is directly proportional to the porosity and moisture content of the concrete. Although it is not a form of corrosion, it can play a definite role in the rebar corrosion. When steel reinforcement is encased in concrete or masonry, the steel is protected by the concrete's protective cover and the alkalinity of concrete or masonry. The alkaline in the concrete and mortar causes a passivation film to surround the steel, and that film protects the steel from the environment the same way it does for aluminum, zinc, and copper.

It takes a relatively high pH to protect the steel. Typically, the pH of concrete ranges from approximately 12 to 14, and the possibility for steel corrosion increases if the pH falls below approximately 10. A pH in the 8-9 range suggests that carbonation is taking place from the concrete surface toward the interior.

Once again, early Americans demonstrated their knowledge of metallurgy when colonial gunsmiths applied the passivating process by using a controlled rusting procedure to produce a very desirable "butternut" brown finish on iron gun barrels as shown in P*hoto 12*. Many early-American gunsmiths had secret browning formulas that usually contained combinations of nitric acid, copper sulfate, wine, and distilled water (one formula even contained urine). The corrosive solution was carefully applied to the highly polished and squeaky-clean barrel and allowed to rust in an undisturbed location for a specific time, depending on desired results. The crust that formed by the rusting was carefully removed to reveal a smooth, brown finish that protected the metal from further corrosion under normal conditions. Bluing is a similar process.

When concrete is fresh, steel reinforcement is protected from corrosion by the high alkalinity of the surrounding cement paste. The protective layer of concrete is stable and adherent in its normal range of alkalinity. However, the alkali in concrete eventually reacts with acidic components in the atmosphere, particularly carbon dioxide in the concrete. This reduces the alkalinity of the concrete by converting the calcium hydroxide to calcium carbonate, which reduces the pH value of the concrete below 10 where the concrete loses its protective ability. When concrete or any other cementitious material in contact with the embedded steel reinforcing is carbonated, the steel surface loses its passivity protection. Now it is possible for corrosion to begin or resume when moisture and oxygen gain access to the steel surface.

The rate of carbonation is mainly influenced by the permeability and the calcium content of the concrete, as well as by the ambient atmospheric conditions—the amount of carbon dioxide, relative humidity, and temperature. Also, concrete can carbonate more rapidly in a hot climate than in a moderate climate.

Edward Gerns' article "Corrosion: The Use of Metal Within Masonry Wall Systems and Associated Life-Cycle Issues," published in the March 2010 issue of *Interface*, is an excellent resource of how ferrous metals behave in masonry construction.

Protective Coatings

Protective coatings provide a common method of corrosion control by separating corrosive materials from potentially corrosive conditions. All protective coatings will provide some protection, but some do it significantly better than others. Anodized aluminum, galvanizing, and factory-applied Kynar®-type finishes can be included in the protective coatings category. To be effective, a protective coating should have the following properties:

- Be matched to the environment and substrate
- Be compatible with cathodic protection if used
- Be abrasion-resistant to resist damage from routine handling
- Electrically isolate the substrate metal from corrosive conditions
- Resist deterioration due to the environment and service temperature
- Have sufficient adhesion to resist under-film migration of an electrolyte
- Be flexible to resist cracking from substrate movement and thermal stress

Photos 13 and *14* show the results of structural steel components that received a marginal shop primer and were not properly protected during on-site staging. *Photo 14* shows what happens when the corrosive process in a textile plant breaks down the protective coatings and attacks the steel structure.

In the unlikely event that extreme pH levels or known corrosive chemicals are present and cannot be avoided, there are several simple solutions to avoid possible damage, such as ammonization and cathodic protection.

Corrosion is a thirst monger, and swimming pools are a Mecca for corrosion. It thrives on moisture—whether from an opening in a façade, from the atmosphere, or a vapor from a structure's normal breathing. When selecting materials associated with indoor swimming, wading, and therapeutic pools, careful consideration should be given to the ambient conditions around the pool and chemical storage areas. Excluding splash and spills, materials and components can be exposed to ambient air that is warm, humid, and usually contains traces of the chemicals (often chlorine) used in the pool water. These are ideal conditions for both galvanic and atmospheric corrosion.

Fountains are not normally heated, but they often contain antifungal chemicals; and outdoor fountains usually contain antifreezing chemicals in addition to antifungal chemicals, all of which can be very corrosive. It is prudent to find out the chemical additives in the water and plan accordingly.

CONCLUSION

Even though new alloys and protective coatings are being developed, corrosion principles have not changed since the days sorcerers were practicing alchemy. Corrosion cannot be completely eliminated, but common sense and diligence can keep it in check. If not controlled, a mild case of corrosion can become a pandemic. However, corrosion can be controlled by thoughtful consideration of details, materials selection, and ambient conditions.

REFERENCES AND ADDITIONAL READING

Joseph Bosich, *Corrosion Prevention for Practicing Engineers*, Barnes and Noble, 1970.

Cris Crissinger, "Considerations for Coastal Coatings, Part 1," *Interface*, RCI, Inc., March 2007.

Cris Crissinger, "Considerations for Coastal Coatings, Part 2," *Interface*, RCI, Inc., June 2007.

Cris Crissinger, "Considerations for Coastal Coatings, Part 3," *Interface*, RCI, Inc., July 2007.

Edward Gerns, "Corrosion: The Use of Metal Within Masonry Wall Systems and Associated Life-Cycle Issues," *Interface*, RCI, Inc., March 2010.

Charles G. Munger, *Corrosion Prevention by Protective Coatings*, National Association of Corrosion Engineers (NACE), 1984.

L.S. Van Delinder, *Corrosion Basics: An Introduction*, NACE, 1984.

Voluntary Guide Specification and Inspection Methods for Clear Anodic Finishes for Architectural Aluminum, AAMA A607.1, American Association of Architectural Metals.

Joseph ("Cris") Crissinger, CCS, CCCA, ASQ

Joseph ("Cris") Crissinger is semiretired and is a construction specifications and materials consultant in Spartanburg, SC. His responsibilities include construction specifications, materials analysis, field investigations, and facility assessments. Crissinger is a Certified Construction Specifier and a Certified Construction Contracts Administrator. He is a member of the Construction Specifications Institute, the Building Performance Committee of ASTM, and the Design and Construction Division of the American Society for Quality. He is a two-time recipient of RCI's Richard Horowitz Award. He also serves in the community on the Construction Board of Appeals for Spartanburg, SC, and is a U.S. submarine veteran. Crissinger may be reached at specalyze@reagan.com.