Corrosion

CEU 256

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Note: In determining your answers to the CE questions, use only the material presented in the corresponding continuing education article. Using information from other materials may result in a wrong answer.

Corrosion is the degradation of a material by its environment. In the case of metals, corrosion is an electrochemical reaction between a metal and its environment. For iron piping, the iron reacts with oxygen to form iron oxide, or rust, which is the basic constituent of the magnetic iron ore (hematite) from which the iron was refined. The many processes necessary to produce iron or steel pipe—from refining through rolling, stamping, and fabricating to the finished product—all impart large amounts of energy to the iron. The iron in a finished pipe is in a highly energized state and reacts readily with oxygen in the environment to form rust. Corrosion results from a flow of direct current through an electrolyte (soil or water) from one location on the metal surface to another location on the metal surface. The current flow is caused by a voltage difference between the two locations.

This chapter covers the fundamentals of corrosion as they relate to a building's utility systems, essentially dealing with piping materials for the conveyance of fluids, both liquid and gas. These pipes are installed either below- or aboveground, thus making the external environment of the pipe earth or air respectively. The internal environment is the fluid conveyed inside the pipe. Many environmental conditions may affect the performance of any given piping material.

FUNDAMENTAL CORROSION CELL

Corrosion is, in effect, similar to a dry cell battery. For corrosion to occur, four elements must be present: an electrolyte, an anode, a cathode, and a return circuit. The electrolyte is an ionized material, such as earth or water, capable of conducting an electric current.

Figure 8-1 shows the actual corrosion cell. Figure 8-2 (practical case) shows the current flows associated with corrosion. The current flows through the electrolyte from the anode to the cathode. It returns to the anode through the return circuit. Corrosion occurs wherever the current leaves the metal and enters the electrolyte. The point where the current leaves the metal is the anode. Corrosion, therefore, occurs at the anode. The current is then picked up at the cathode. No corrosion occurs here, as the cathode is protected against corrosion (the basis of cathodic protection). Polarization (hydrogen film buildup) occurs at the cathode. The flow of the current is caused by a potential (voltage) difference between the anode and the cathode.

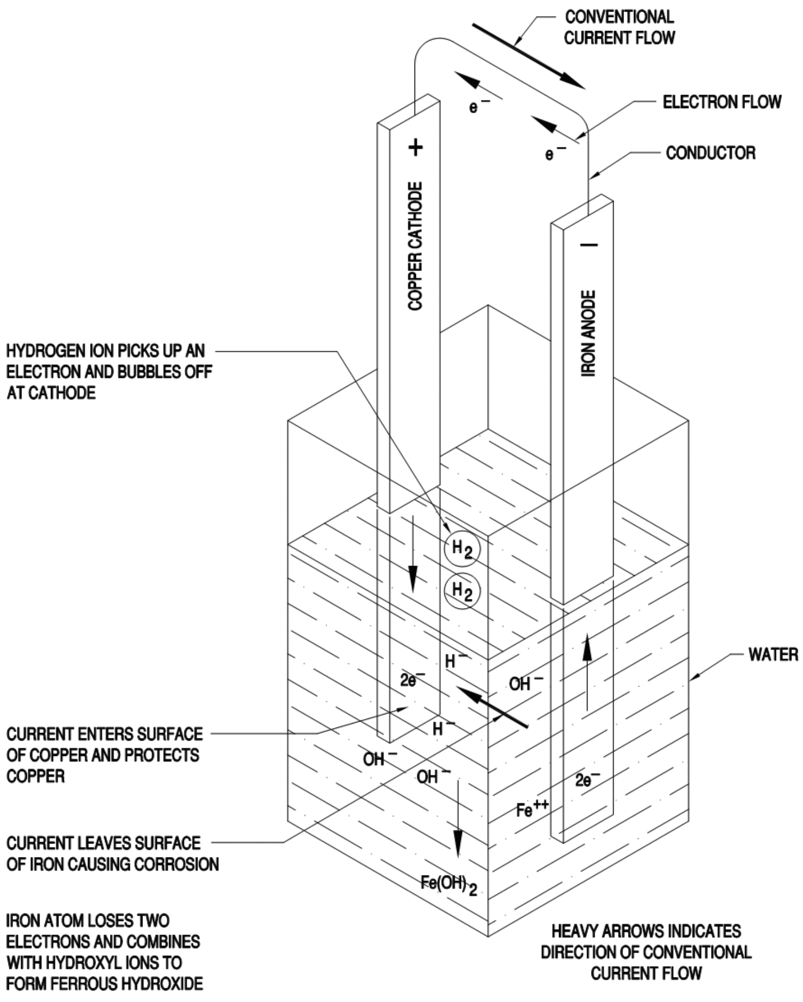

Figure 8-1 Basic Corrosion Cell

Electrochemical Equivalents

Dissimilar metals, when coupled together in a suitable environment, will corrode according to Faraday's law—that is, 26.8 ampere-hours (A-h), or 96,500 coulombs (C), are required to remove 1 gram-equivalent of the metal. At this rate of attack, the amount of metal that is removed by a current of 1 A flowing for one year is shown in Table 8-1.

Table 8-1 Electrochemical Metal Losses of Some Common Metals

Metal	Loss, lb/A-yr (kg/C)[a]
Iron (Fe2+)	20.1 (72.4)
Aluminum (Al3+)	6.5 (23.4)
Lead (Pb2+)	74.5 (268.3)
Copper (Cu2+)	45.0 (162.0)
Zinc (Zn2+)	23.6 (85.0)
Magnesium (Mg2+)	8.8 (31.7)
Nickel (Ni2+)	21.1 (76.0)
Tin (Sn+)	42.0 (151.2)
Silver (Ag+)	77.6 (279.4)
Carbon (C4+)	2.2 (7.9)

[a] A = Ampere; C = Coulomb, the amount of electric charge transported in one second by a steady current of 1 ampere

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COMMON FORMS OF CORROSION

Corrosion occurs in a number of common forms.

Uniform Attack

Uniform attack (Figure 8-3) is the most common form of corrosion and is characterized by a general dissolving of the metal wall. The material and its corrosion products are readily dissolved in the corrosive media.

Pitting Corrosion

Pitting corrosion (Figure 8-4) is usually the result of the localized breakdown of a protective film or layer of corrosion products. Anodic areas form at the breaks in the film, and cathodic areas form at the unbroken portions of the film. The result is localized, concentrated corrosion, which forms deep pits.

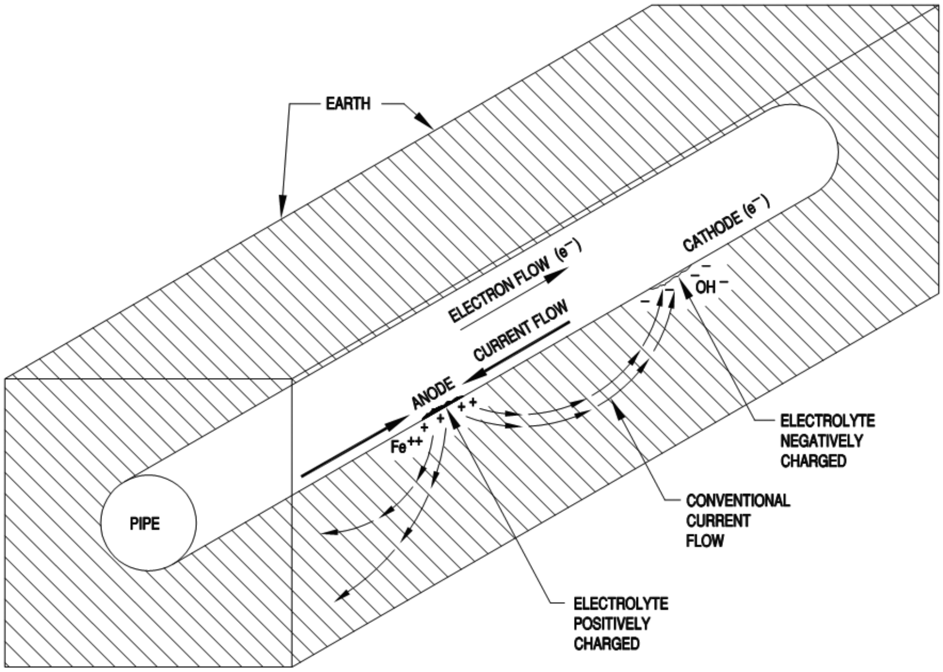

Figure 8-2 Basic Cell Applied to an Underground Structure

Galvanic Corrosion

Galvanic corrosion (Figure 8-5) occurs when two dissimilar metals are in contact with an electrolyte. The example shown is iron and copper in a salt solution, with the iron being the anode corroding toward the copper cathode. The driving force of this corrosion is the difference in cell potential, or electromotive force, of the metals, which drives the electrons from one metal to the other.

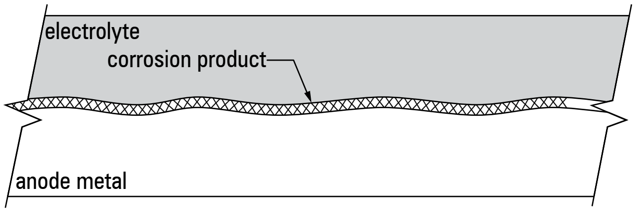

Figure 8-3 Uniform Attack

Concentration Cell Attack

Concentration cell attack (Figure 8-6) is caused by differences in the concentration of a solution, such as differences in oxygen concentration or metal-ion concentration. These can occur in crevices, as shown in the example, or under mounds of dirt, corrosion products, or contamination on the metal surface. The area of low oxygen or metal-ion concentration becomes anodic to areas of higher concentration.

Crevice corrosion is a form of concentration cell attack.

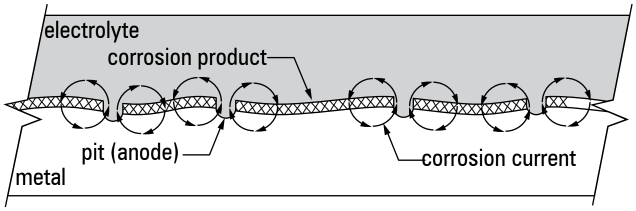

Figure 8-4 Pitting Corrosion

Impingement Attack

Impingement attack, or erosion corrosion (Figure 8-7), is the result of turbulent fluid at high velocity breaking through protective or corrosion films on a metal surface. The corrosion usually forms in a definite direction.

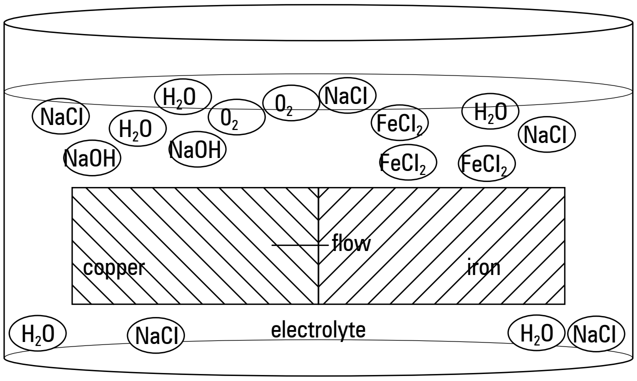

Figure 8-5 Galvanic Corrosion

Stress Corrosion Cracking

Stress corrosion cracking (Figure 8-8) results from placing highly stressed parts in corrosive environments. Corrosion causes concentration of the stress, which eventually exceeds the yield strength of the material, and cracking occurs.

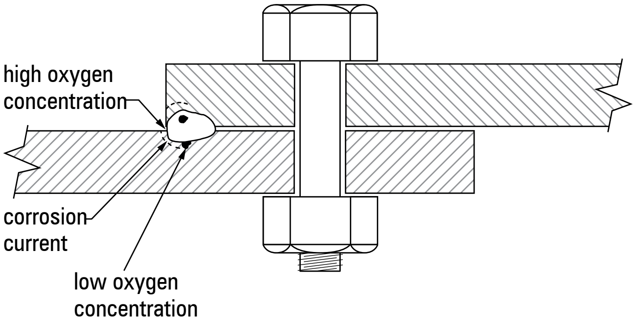

Figure 8-6 Concentration Cells

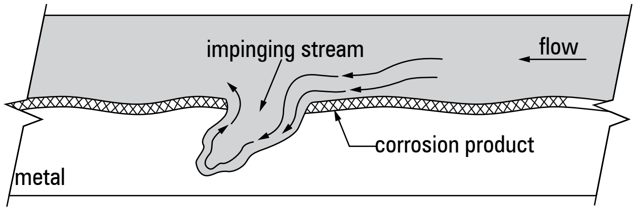

Figure 8-7 Impingement Attack

Selective Attack

Selective attack, or leaching (Figure 8-9), is the corrosive destruction of one element of an alloy. Examples are dezincification of brass and graphitization of cast iron.

Stray Current

Stray current corrosion (Figure 8-10) is caused by the effects of a direct current source such as a cathodic protection rectifier. A protective current may be picked up on a pipeline or structure that is not part of the protected system. This current follows to the other structure and at some point leaves the other structure and travels through the electrolyte (soil or water) back to the protected structure. This causes severe corrosion at the point of current discharge.

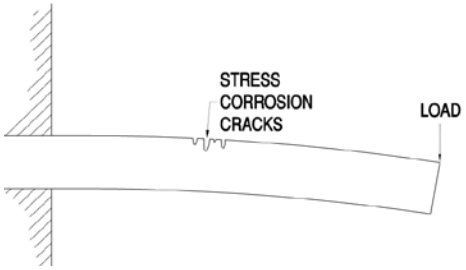

Figure 8-8 Stress Corrosion

Corrosion by Differential Environmental Conditions

Examples of differential environmental cells are shown in Figure 8-11. It should be noted that variations in moisture content, availability of oxygen, change in soil resistivity, or variations of all three may occur in some cases. As in all corrosion phenomena, changes or variations in the environment are a contributing factor.

Figure 8-9 (A) Plug-Type Dezincification (B) Layer-Type Dezincification

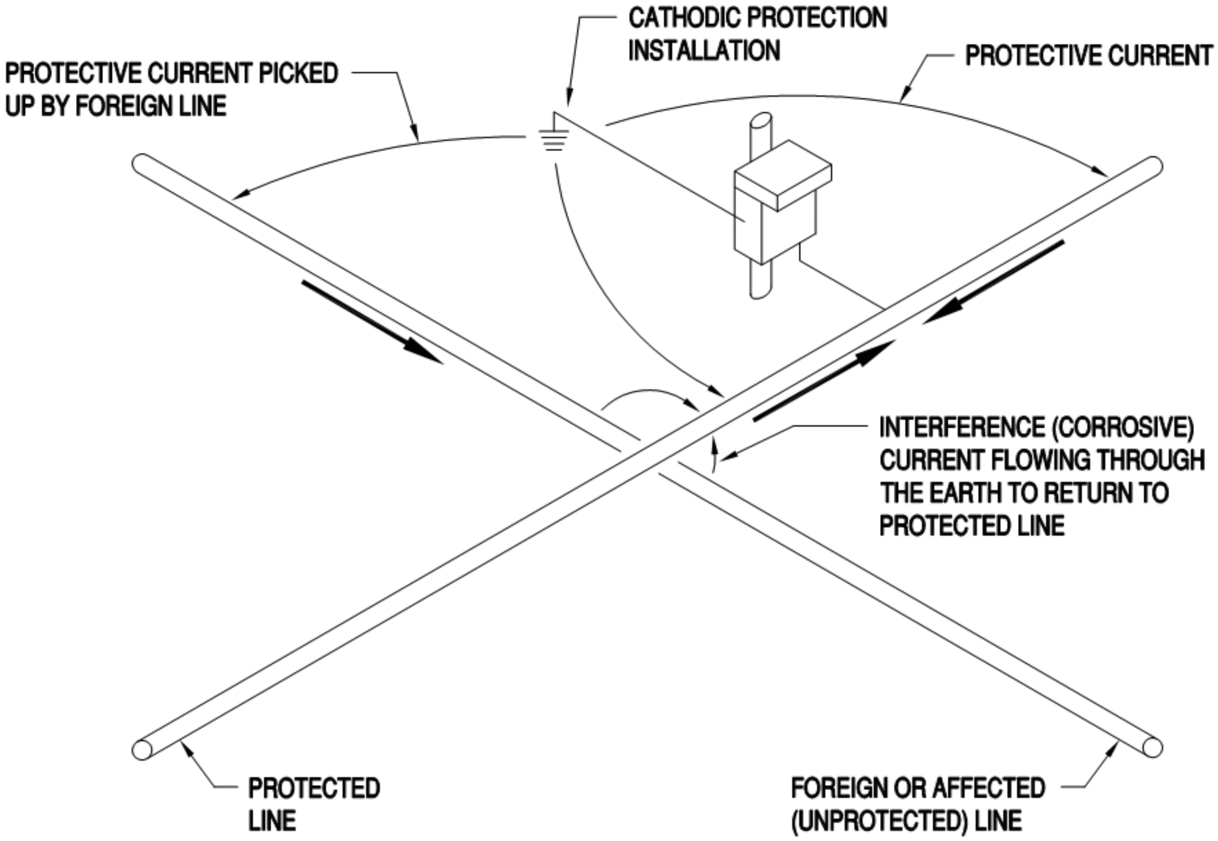

Figure 8-10 Stray Current Corrosion

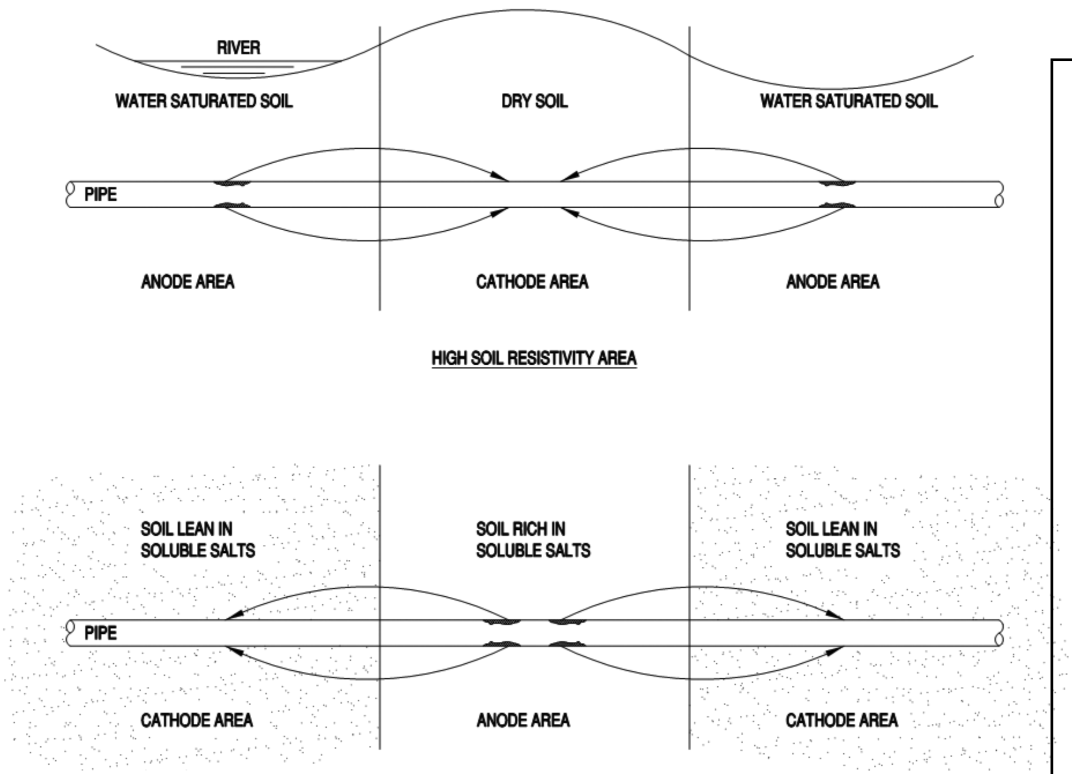

Figure 8-11 Corrosion by Differential Environmental Conditions

THE GALVANIC SERIES

The galvanic series of metals in seawater, listed in Table 8-2, is useful in predicting the effects of coupling various metals. Actual tests at different temperatures and in different environments may yield slightly different results. Metals that are far apart in the series have a greater potential for galvanic corrosion than do metals in the same group or metals near each other in the series. Metals listed above other metals in the series are generally anodic (corrode) to metals listed below them. The relative area of the metals in the couple must be considered along with the polarization characteristic of each metal. To avoid corrosion, a large anode area with a small cathode area is favorable.

Table 8-2 Standard Galvanic Series of Common Metals in Seawater

Anodic End (most corrodible)
Magnesium
Magnesium Alloys
Zinc
Galvanized Steel
Aluminum 5052H
Aluminum 3004
Aluminum 3003
Aluminum 1100
Aluminum 6053
Alcad Aluminum Alloys
Cadmium
Aluminum 2017
Aluminum 2024
Low-carbon Steel
Wrought Iron
Cast Iron
Ni-Resist
Type 410 Stainless Steel (active)
50Sn-50Pb Solder
Type 304 Stainless Steel (active)
Type 316 Stainless Steel (active)
Lead
Tin
Muntz Metal (C28000)
Manganese Bronze (C67500)
Naval Brass (C46400)
Nickel (active)
Inconel (active)
Cartridge Brass (C26000)
Admiralty Metal (C44300)
Aluminum Bronze (C61400)
Red Brass (C23000)
Copper (C11000)
Silicon Bronze (C65100)
Copper Nickel, 30% (C71500)
Nickel (passive)
Inconel (passive)
Monel
Type 304 Stainless Steel (passive)
Type 316 Stainless Steel (passive)
Brazing Filler Metals (silver-copper-zinc alloys)
Silver
Gold
Platinum
Cathodic End

ELECTROMOTIVE FORCE SERIES

An electromotive force is defined as a force that tends to cause a movement of electrical current through a conductor. Table 8-3, known as the electromotive force series, lists the metals in their electromotive force order and defines their potential with respect to a saturated copper-copper sulfite half-cell. This list is arranged according to standard electrode potentials, with positive potentials (greater than 1) for elements that are cathodic to a standard hydrogen electrode and negative potentials (less than 1) for elements that are anodic to a standard hydrogen electrode.

In most cases, any metal in this series will displace the more positive metal from a solution and thus corrode to protect the more positive metal. There are exceptions to this rule because of the effect of ion concentrations in a solution and because of the different environments found in practice. This exception usually applies to metals close together in the series, which may suffer reversals of potential. Metals far apart in the series will behave as expected; the more negative will corrode to the more positive.

In an electrochemical reaction, the atoms of an element are changed to ions. If an atom loses one or more electrons (e^-), it becomes an ion that is positively charged and is called a cation (example: Fe^{2+}). An atom that takes on one or more electrons also becomes an ion, but it is negatively charged and is called an anion (example: OH^-). The charges coincide with the valence of the elements.

The arrangement of a list of metals and alloys according to their relative potentials in a given environment is a galvanic series. By definition, a different series could be developed for each environment.

FACTORS AFFECTING THE RATE OF CORROSION

The rate of corrosion is directly proportional to the amount of current leaving the anode surface. This current is related to both the potential (voltage) between the anode and cathode and the circuit resistance. Voltage, resistance, and current are governed by Ohm's law, shown in Equation 8-1.

EQUATION 8-1

$$I = \frac{E}{R}$$

where:

I = Current, A or mA
E = Voltage, V or mV
R = Resistance, ohm (Ω)

Essentially, Ohm's law states that current is directly proportional to the voltage and inversely proportional to the resistance.

Effect of the Metal Itself

For a given current flow, the rate of corrosion of a metal depends on Faraday's law, shown in Equation 8-2.

EQUATION 8-2

$$w = KIt$$

where:

w = Weight loss
K = Electrochemical equivalent
I = Current
t = Time

For practical purposes, the weight loss typically is expressed in pounds per ampere year (kilograms per coulomb). Loss rates for some common metals are given in Table 8-4. For example, if 1 ampere is discharged from a steel pipeline over a period of one year, 20 pounds (6.1 kilograms) of steel will be lost.

Corrosion of metals in aqueous solutions also is influenced by the following factors: acidity, oxygen content, film formation, temperature, velocity, and homogeneity of the metal and the electrolyte. These factors are discussed below, since they are factors that can be measured or detected by suitable instruments.

Acidity

The acidity of a solution represents the concentration of hydrogen ions, or the pH. In general, low pH (acid) solutions are more corrosive than neutral (7.0 pH) or high pH (alkaline) solutions. Iron and steel, for example, suffer accelerated corrosion in solutions where the pH is 4.5 or less. Exceptions to this rule are amphoteric materials such as aluminum and lead, which corrode more rapidly in alkaline solutions.

Table 8-3 Electromotive Force Series

Metal	Potential of Metals
Magnesium (galvomag alloy)[a]	1.75
Magnesium (H-I alloy)[a]	1.55
Zinc	1.10
Aluminum	1.01
Cast iron	0.68
Carbon steel	0.68
Stainless steel type 430 (17% Cr)[b]	0.64
Ni-resist cast iron (20% Ni)	0.61
Stainless steel type 304 (18% Cr, 8% Ni)[b]	0.60
Stainless steel type 410 (13% Cr)[b]	0.59
Ni-resist cast iron (30% Ni)	0.56
Ni-resist cast iron (20% Ni$^+$Cu)	0.53
Naval rolled brass	0.47
Yellow brass	0.43
Copper	0.43
Red brass	0.40
Bronze	0.38
Admiralty brass	0.36
90:10 Cu-Ni$^+$ (0.8% Fe)	0.35
70:30 Cu-Ni$^+$ (0.06% Fe)	0.34
70:30 Cu-Ni$^+$ (0.47% Fe)	0.32
Stainless steel type 430 (17% Cr)[b]	0.29
Nickel	0.27
Stainless steel type 316 (18% Cr, 12% Ni, 3% Mo)[b]	0.25
Inconel	0.24
Stainless steel type 410 (13% Cr)[b]	0.22
Titanium (commercial)	0.22
Silver	0.20
Titanium (high purity)	0.20
Stainless steel type 304 (18% Cr, 8% Ni)[b]	0.15
Hastelloy C	0.15
Monel	0.15
Stainless steel type 316 (18% Cr, 12% Ni, 3% Mo)[b]	0.12

Note: Based on potential measurements in sea water, velocity of flow 13 ft/s (3.96 m/s), temperature 77°F (25°C).

[a] Based on data provided by the Dow Chemical Co.

[b] The stainless steels, as a class, exhibited erratic potentials depending on the incidence of pitting and corrosion in the crevices formed around the specimen supports. The values listed represent the extremes observed and, due to their erratic nature, should not be considered as establishing an invariable potential relation among the alloys that are covered.

Oxygen Content

The oxygen content of aqueous solutions causes corrosion by reacting with hydrogen at the metal surface to depolarize the cathode, resulting in the exposure of additional metal. Iron and steel corrode at a rate proportional to the oxygen content. Most natural waters originating from rivers, lakes, and streams are saturated with oxygen. Reduction of oxygen is a part of the corrosion process in most of the corrosion found in practice. The possibility of corrosion being influenced by atmospheric oxygen should not be overlooked in design work.

Film Formation

Corrosion and its progress often are controlled by the corrosion products formed on the metal surface. The ability of these films to protect metal depends on how they form when the metal is originally exposed to the environment. Thin, hard, dense, tightly adherent films afford protection, whereas thick, porous, loose films allow corrosion to proceed without providing any protection. As an example, the iron oxide film that usually forms on iron pipe in contact with water is porous and easily washed away to expose more metal to corrosion. The effective use of corrosion inhibitors in many cases depends on the type of film it forms on the surface to be protected.

Table 8-4 Corrosion Rates for Common Metals

Metal	Loss Rate, lb/A-yr (kg/C)[a]
Iron or steel	20 (6.1)
Lead	74 (22.5)
Copper	45 (162.0)
Zinc	23 (7.0)
Aluminum	6.5 (23.4)
Carbon	2.2 (7.9)

[a] A = Ampere; C = Coulomb, the amount of electric charge transported in one second by a steady current of 1 ampere

Temperature

The effect of temperature on corrosion is complex because of its influence on other corrosion factors. Temperature can determine oxygen solubility, the content of dissolved gases, and the nature of protective film formation, thereby resulting in variations in the corrosion rate.

Generally, in aqueous solutions, higher temperatures increase corrosion rates. In domestic hot water systems, for example, corrosion rates double for each 10°F (6°C) rise above 140°F (60°C) water temperature. Temperature also can reverse potentials, such as in the case of zinc-coated iron at approximately 160°F (71°C) water temperature, when the zinc coating can become cathodic to the iron surface, accelerating the corrosion of iron.

Velocity

In many cases, velocity of the solution controls the rate of corrosion. Increasing velocity usually increases corrosion rates. The more rapid movement of the solution causes corrosion chemicals, including oxygen, to be brought into contact with the metal surface at an increased rate, and corrosion products or protective films are carried away from the surface at a faster rate.

Another important effect of high velocity is that turbulence can result in local differential oxygen cells or metal-ion concentration cells, causing severe local attack. High velocities also tend to remove protective films, causing rapid corrosion of the metal surfaces.

Homogeneity

The homogeneity of the metal and of the electrolyte is extremely important to corrosion rates. In general, nonhomogeneous metals or electrolytes cause local attack or pitting, which occurs at concentrated areas and is, therefore, more serious than the general overall corrosion of a material. Examples include concentration cells, galvanic cells, microstructural differences, and differences in temperature and velocity.

CORROSION CONTROL

Corrosion control is the regulation, control, or prevention of a corrosion reaction for a specific goal. This may be accomplished through any one or a combination of the following factors:

- Materials selection
- Design to reduce corrosion
- Passivation
- Coating
- Cathodic protection
- Inhibitors (water treatment)

Materials Selection

Materials selection is the most common method of preventing corrosion. Corrosion resistance, along with other important properties, must be considered in selecting a material for any given environment. When a material is to be specified, the following steps should be used:

1. Determine the application requirements.
2. Evaluate possible material choices that meet the requirements.
3. Specify the most economical method.

Factors to be considered include:

- Material cost
- Corrosion-resistance data
- Ability to be formed or joined by welding or soldering
- Fabricating characteristics (bending, stamping, cutting, etc.)
- Mechanical properties (tensile and yield strength, impact resistance, hardness, ductility, etc.)
- Availability of material
- Electrical or thermal properties
- Compatibility with other materials in the system
- Specific properties, such as nuclear radiation absorption and low- or high-temperature properties

Initial cost is an important consideration, but the life cost as applied to the system, as a whole, is more important. For example, if an inexpensive part must be replaced periodically, the cost of downtime and labor to install it may make the inexpensive part the most expensive part when all factors are considered.

Design to Reduce Corrosion

Corrosion can be eliminated or substantially reduced by incorporating some basic design suggestions. The following design suggestions can minimize corrosive attack.

- Provide dielectric insulation between dissimilar metals, when dissimilar metals such as copper and steel are connected together (e.g., at a water heater). In a pipeline, for example, dielectric insulation should be installed to prevent contact between the two metals. Without such insulation, the metal higher in the galvanic series (steel) will suffer accelerated corrosion because of the galvanic cell between copper and steel. When designing systems requiring dissimilar metals, the need for dielectric insulation should be investigated.
- Avoid surface damage or marking. Areas on surfaces that have been damaged or marked can initiate corrosion. These areas usually become anodic to the adjacent untouched areas and can lead to failures. The designer should consider this when machining or fabrication is needed so unnecessary damage does not occur.

- Do not use excessive welding or soldering heat. Areas that are heated excessively during welding or soldering can result in changes to a metal's microstructure. Large grain growth can result in accelerated corrosion. The grain growth changes the physical properties of the metal and results in nonhomogeneity of the metal wall. Designs can minimize this effect by using heavier wall thicknesses in areas to be welded.
- Crevices should be avoided. Concentration cells usually form in crevices and can cause premature failures. Regardless of the amount of force applied in bolting two plates together, it is not possible to prevent gradual penetration of liquid into the crevice between the plates. This forms concentration cells where the fluid in the crevices is depleted and forms anodic areas. The most practical way of avoiding crevices is to design welded connections in place of mechanical fasteners.
- Avoid heat or chemicals near metal walls.
- Prevent the condensation of moisture from the air on cold metal surfaces. The cold metal surface should be thermally insulated if possible.
- Install beams, angles, etc. so they drain easily and cannot collect moisture, or provide drain holes.

Passivation

Passivation is the accelerated formation of a protective coating on metal pipe (primarily stainless steel) by contact with a chemical specifically developed for this purpose. A thin protective film is formed when reacting and bonding to the metal. This occurs at the point of potential metal loss (corrosion).

Passivation prevents corrosion in the remaining pits left from free machining and the residual that gets trapped therein. Sulfides and iron particles act as initiation sites to corrosion. It is not a scale removal method; thus, surface cutting tool contaminants need to be removed prior to the passivation process. The use of citric acid for passivation is an alternate to using nitric acid in the stainless steel industry. Due to it being safe, organic, and easy to use, citric acid has gained popularity.

Care must be taken to ensure the balance of time, temperature, and concentrations to avoid flash attack, which is caused by contaminated passivating solutions containing high levels of chlorides. Flash attack causes a heavily etched, dark surface rather than an oxide film to occur. Passivating solutions should be free of contaminants to prevent this from happening.

New methods are being discovered and tested to protect other material surfaces such as aluminum. Periodic testing after passivation ensures that the metal surfaces are maintained.

Coating

Materials exposed to the atmosphere that do not have the ability to form natural protective coatings, such as nickel and aluminum, are best protected by the application of an artificial protective coating. The coating is applied to keep the corroding material from the surface at all times.

One of the most important considerations in coating application is surface preparation. The surface must be properly cleaned and free of scale, rust, grease, and dirt to allow the coating to bond properly to the surface. The best coating in the world will give unsatisfactory results if the surface is poorly prepared. The surface may require pickling, sandblasting, scratch brushing, or flame cleaning to properly prepare it for application of a coating.

The actual coating that is applied depends on the application and may be either metallic (such as galvanizing) or nonmetallic organic (such as vinyl or epoxy). The coating may actually be a coating system, such as primer, intermediate coat (to bond primer and top coat), and finish or top coat. Coating manufacturers' literature should be consulted regarding coating performance, surface preparatory application, and handling of coated surfaces.

For atmospheric exposure, coatings alone are relied on to provide protection in many applications. Coatings by themselves, however, are not considered adequate for corrosion control of buried or submerged structures because there is no such thing as a perfect coating. All coatings have inherent holes or holidays. Often the coating is damaged during installation or adjacent construction. Concentrated corrosion at coating breaks often causes failures sooner on coated structures than on bare ones. In stray current areas, severe damage occurs frequently on coated pipe because of the high density of discharge current at coating faults.

The most important function of coating is in its relation to cathodic protection. Cathodic protection current requirements, and hence operating costs, are proportional to the amount of bare surface exposed to the soil. When structures are coated, it is necessary to protect only the small areas of coating faults. Careful applications of coating and careful handling of coated structures lead to maximum coating effectiveness, thus minimizing protective current requirements and costs. Also, lower current usage generally means less chance of stray current effects on other structures.

Cathodic Protection

Cathodic protection is an effective tool to control corrosion of metallic structures, such as water lines and tanks buried or immersed in a continuous electrolyte, by making the metal structure the cathode and applying direct current from an anode source. By making the entire structure the cathode, all anode areas from the local corrosion cells are eliminated, and DC current is prevented from leaving the structure, thereby stopping further corrosion.

The most common sacrificial anode is made of magnesium. Magnesium has the highest natural potential of the metals listed in the electromotive series and, therefore, the greatest current-producing capacity of the series. Zinc anodes sometimes are used in very low-resistivity soils where current-producing capacity such as that of magnesium is not required.

The two proven methods of applying cathodic protection are with galvanic anodes and impressed current systems. The basic difference between the two types of protection is as follows: The galvanic anode system depends on the voltage difference generated between the anode material and the structure material to cause a flow of DC current to the structure. The impressed current system utilizes an AC/DC rectifier to provide current to relatively inert anodes and can be adjusted to provide the necessary voltage to drive the required current to the structure's surfaces. Choice of the proper system depends on a number of factors. Each has its advantages, which are discussed below.

Galvanic Anodes

Galvanic anodes are used most advantageously on coated structures in low soil resistivity where current requirements are low. Some advantages of using galvanic anodes are as follows:

- It has a relatively low installation cost.
- No external power source is required.
- It does not require much maintenance.
- It does not adversely affect foreign structures.
- It can be installed with pipe, minimizing right-of-way cost.

Some disadvantages of using galvanic anodes are as follows:

- Driving voltage is low (approximately 0.15 V).
- Current output is limited by soil resistivity.
- It's not applicable for large current requirements.

The galvanic anode system of an active metal anode, such as magnesium or zinc, is placed in the electrolyte (soil or water) near the structure and connected to it with a wire. This is illustrated in Figures 8-12 and 8-13. Cathodic protection is achieved by current flow due to the potential difference between the anode (metal) and the cathode (structure). A corrosion cell or battery is created, and current flows from the corroding anode material through the soil to the cathode or protected structure. Hence, the galvanic anode is caused deliberately to waste itself to prevent corrosion of the protected structure. Because the galvanic anode system relies on the difference in voltage between two metals, which in most cases is limited to 1 V or less, the current generated by the anodes is usually low (approximately 0.1 to 0.5 A per anode).

Galvanic anode systems usually are used for structures having small current requirements, such as well-coated, small-diameter pipes, water heaters, sewage lift stations, some offshore structures, and structures in congested areas where currents must be kept low to avoid detrimental effects on other structures. Galvanic anodes may be installed in banks at specific locations. They are, however, usually distributed around protected structures because of their limited current output.

As an example, considering a pipe-to-soil potential of 0.85 V as protection for a steel pipeline, the driving potential for zinc anodes is 0.25 V and for magnesium is 500 A-h/lb (1,795 C/kg). The actual life of anodes of a given weight at a known current output can be calculated using the following formulas:

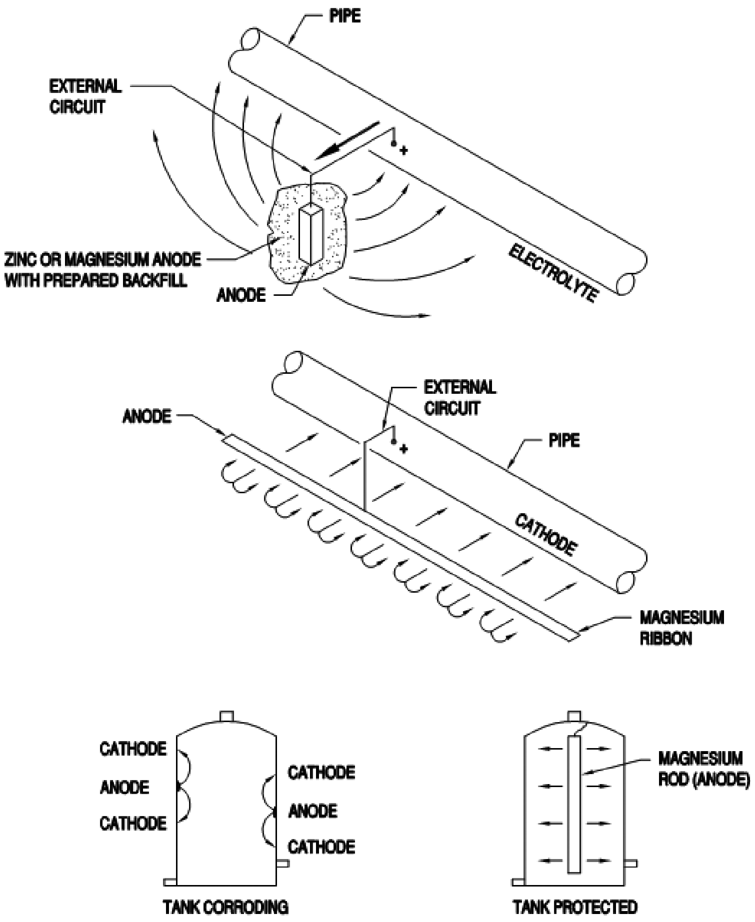

Figure 8-12 Cathodic Protection by the Sacrificial Anode Method

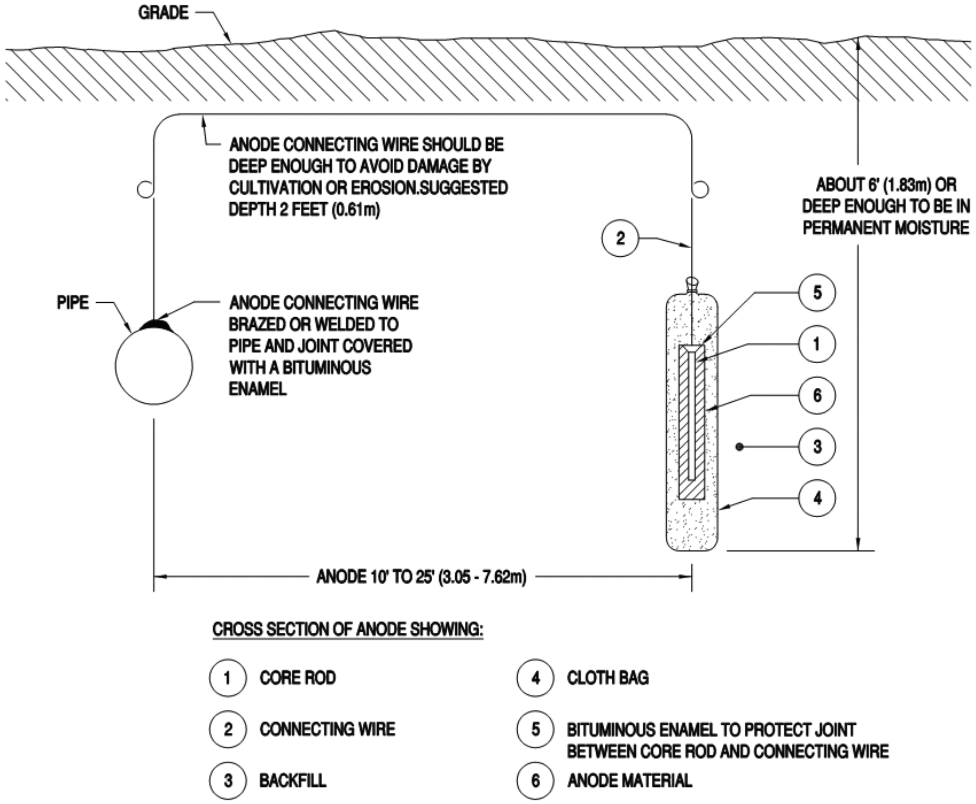

Figure 8-13 Typical Sacrificial Anode Installation

EQUATION 8-3

$$LM = \frac{57.08 \times w}{i}$$

EQUATION 8-4

$$LZ = \frac{38.2 \times w}{i}$$

where:

LM = Life of magnesium anode, years
LZ = Life of zinc anode, years
w = Weight of anode, lb (kg)
i = Output of anode, mA

The controlling factor for current output of zinc and magnesium anodes is soil resistivity. When soil resistivity is known or determined, then the current output of variously sized anodes for either magnesium or zinc can be estimated as follows:

EQUATION 8-5

$$iM = \frac{150{,}000 \times f}{p}$$

EQUATION 8-6

$$iZ = \frac{150{,}000 \times f \times 0.27}{p}$$

where:

iM = Current output of magnesium, mA
iZ = Current output of zinc, mA
p = Soil resistivity, Ω-cm
f = Anode size factor

The cost of galvanic cathodic protection generally favors the use of zinc anodes over magnesium at soil resistances less than 1,500 ohm-cm and the use of magnesium at soil resistances more than 1,500 ohm-cm.

Impressed Current

The impressed current system, illustrated in Figure 8-14, differs substantially from the galvanic anode system in that it is externally powered, usually by an AC/DC rectifier, which allows great freedom in adjustment of current output. Current requirements of several hundred amperes can be handled by impressed current systems. The impressed current system usually consists of graphite or high-silicon iron anodes connected to an AC/DC rectifier, which, in turn, is wired to the structure being protected. Current output is determined by adjustment of the rectifier voltage to provide current as required. The system is not limited by potential difference between metals, and voltage can be adjusted to provide an adequate driving force to emit the necessary current. Impressed current systems are used for structures having large current requirements, such as bare pipe, tank farms, large-diameter cross-country pipelines, cast iron water lines, and many offshore facilities.

Impressed current cathodic protection has the following advantages:

- Large current output
- Voltage adjustment over a wide range
- Can be used with a high soil resistivity environment
- Can protect uncoated structures
- Can be used to protect larger structures

Impressed current cathodic protection has the following disadvantages:

- Higher installation and maintenance costs
- Power costs

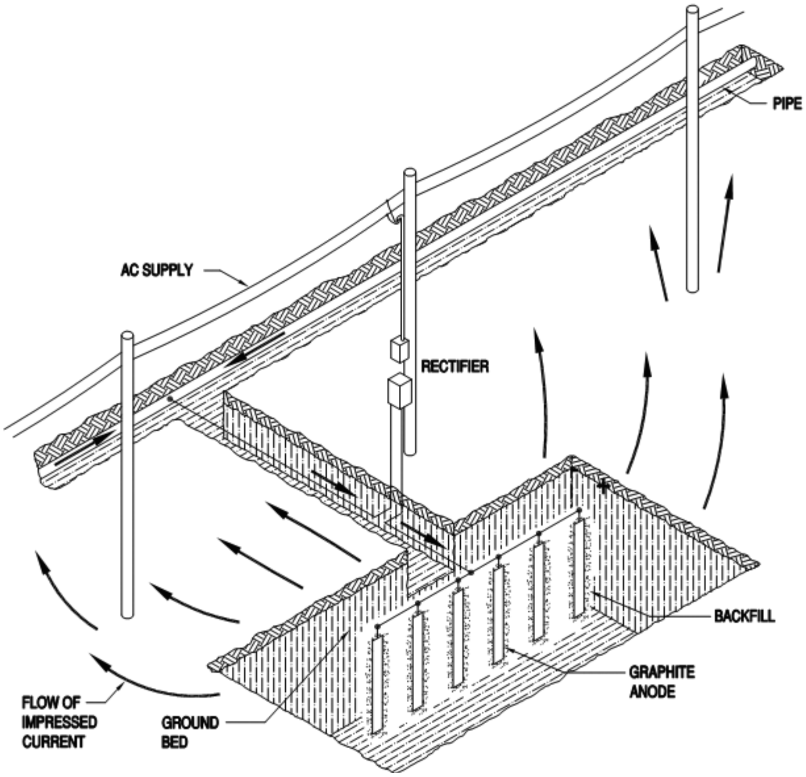

Figure 8-14 Cathodic Protection by the Impressed Current Method

- Can cause adverse effects (stray current) with foreign structures

Solar-powered photovoltaic systems for cathodic protection are now available at a reasonable cost due to advances in the technology. A system consists of solar photovoltaic panels, a charge controller, high capacity batteries, a cathodic protection control unit, and a DC array combiner box as illustrated in Figure 8-15. The system needs to be designed for the particular location, and system performance is modeled taking into account the working temperature, voltage, battery efficiency, system losses, and derating factors. Batteries need to be incorporated in these systems to store excess electrical energy generated by the photovoltaic array during the day to provide power at night or other periods of low sunlight. The batteries' capacity is calculated to provide enough power for normal day-to-day operation at the worst time of year plus a reserve capacity for periods of bad weather. The main advantage of this type of system is the use of solar power, which may work well for remote locations.

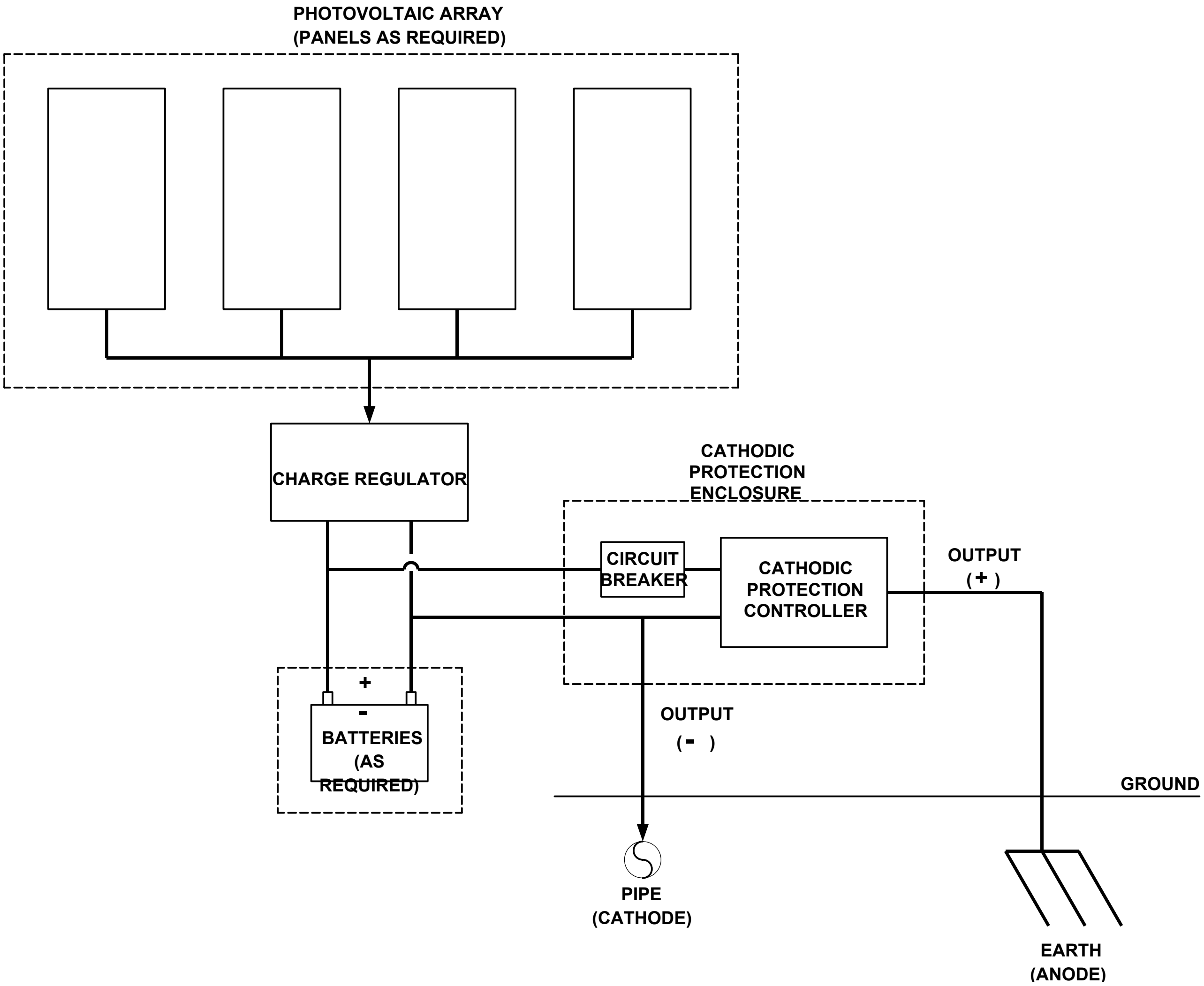

Figure 8-15 Cathodic Protection by the Impressed Current Method Using Solar Power

When designing impressed current cathodic protection systems, the engineer must determine the type and condition of the structure. Obtaining knowledge of the presence or lack of coating, size of the structure, electrical continuity, and location is a necessary first step. Next, the availability of power and ease of installing the ground bed must be determined. It also is generally necessary to perform a current requirement test utilizing a portable DC generator or storage batteries, which defines an apparent DC current requirement to protect the structure. Tests to determine any adverse effects also should be conducted on foreign structures at this time. Any current drained to foreign structures should be added to the current requirements.

After the total current requirement is known, the ground bed is designed so that the circuit resistance is relatively low. Actual ground bed design depends on soil resistivity. A number of empirical formulas are available to determine the number of parallel anodes required for a certain circuit resistance.

Cathodic Protection Criteria

Criteria for determining adequate cathodic protection have been established by the NACE International, The Corrosion Society. These criteria are based on measuring structure-to-electrode potentials with a copper-sulfate reference electrode.

Cathodic protection serves its purpose best, and is by far the most economical, when it is properly coordinated with the other methods of corrosion control, especially coating. In general, the least expensive, easiest to maintain, and most practical system is to apply a good-quality coating to a new structure and then use cathodic protection to eliminate corrosion at the inevitable breaks in the coating. The reason for this is that it takes much more current and anodes to protect bare metal than it does to protect coated metal. The amount of protective current required is proportional to the area of metal exposed to the electrolyte.

In addition to using coatings, it is necessary to ensure continuity of the structures to provide protection of the whole structure. This also prevents undesirable accelerated stray current corrosion to the parts of the structure that are not electrically continuous. Therefore, all non-continuous joints, such as mechanical, push-on, or screwed joints in pipelines, must be bonded. All tanks in a tank farm or piles on a wharf must be bonded to ensure electrical continuity.

Other important components used in effective cathodic protection systems are dielectric insulation and test stations. Dielectric insulation sometimes is used to isolate underground protected structures from aboveground structures to reduce the amount of cathodic protection current required. Care must be taken to avoid short-circuiting (bypassing) the insulation, or protection can be destroyed. Test stations are wires attached to the underground structure (pipeline or tank) to provide electrical contact for the purpose of determining protection effectiveness. Test stations also are used to make bonds or connections between structures when required to mitigate stray current effects.

Costs of Cathodic Protection

Corrosion of underground, ferrous metal structures can be economically controlled by cathodic protection. Cathodic protection costs are added to the initial investment since they are a capital expense. To be economically sound, the spending of the funds must yield a fair return over the expected life of the facility.

Protecting a new facility requires an initial increase of perhaps 10 percent in capital investment. Payout time is usually 10 to 15 years; thereafter, appreciable savings accrue due to this investment, which prevents or reduces the frequency of leaks. Effective corrosion control through the application of cathodic protection reduces the leak frequency for a structure to a minimum with minimum cost.

Cathodic protection systems must be properly maintained. Rectifier outputs must be checked monthly. Changes or additions to the protected structure must be considered to see if changes or additions to the cathodic protection system are required. Annual inspections by a corrosion engineer are required to ensure that all malfunctions are corrected and cathodic protection continues unhampered.

Inhibitors (Water Treatment)

Plant utility services such as boiler feed water, condensate, refrigerants, and cooling water require the addition of inhibitors or water treatment. Boiler feed water must be treated to maintain proper pH control, dissolved solid levels, and oxygen content. Condensate requires treatment to control corrosion by oxygen and carbon dioxide. Brine refrigerants and cooling water in closed-loop circulating systems require proper inhibitors to prevent corrosion.

Water treatment may consist of a simple adjustment of water hardness to produce naturally forming carbonate films. This carbonate film, if properly adjusted, will form to a controlled thickness just sufficient to prevent corrosion by keeping water from contacting the metal surface. In cooling water, where hardness control is not practical, inhibitors or film-forming compounds may be required.

Sodium silicate and sodium hexametaphosphate are examples of film-forming additives in potable water treatment. A tight, thin, continuous film of silica (water glass) or phosphate adheres to the metal surface, preventing pipe contact with the water. (Phosphate additives to potable water are limited or prohibited in some jurisdictions.)

In closed-loop cooling systems and systems involving heat-exchange surfaces, it may not be possible to use film-forming treatment because of the detrimental effects on heat transfer. In these cases, inhibitors are used; these control corrosion by increasing polarization of anodic or cathodic surfaces and are called anodic or cathodic inhibitors respectively. The anodic or cathodic surfaces are covered, preventing completion of the corrosion cell by elimination of either the anode or cathode.

When water treatment or inhibitors are used, a testing program must be established to ensure that proper additive levels are maintained. In some cases, continuous monitoring is required. Also, environmental considerations in local areas must be determined before additives are used or before any treated water is discharged to the sanitary sewer or storm drainage system.

EROSION/CORROSION OF COPPER PIPING SYSTEMS

While copper is well known for its excellent resistance to corrosion, several things can damage copper piping systems. One of the more common causes of damage to a copper piping system is erosion/corrosion.

Erosion/corrosion is a mechanically induced failure, which may be caused by any or all of the following conditions:

- Water at high velocity: An undersized piping system or an oversized circulating pump may cause high water velocity. Installation of a smaller capacity pump or a throttling bypass on the existing pump should help lower the velocity of the water in the system. The recommended velocity for cold water in a copper tube system is 5–8 feet per second (fps). The recommended maximum velocity for hot water in a copper tube system is 4–5 feet per second.
- Numerous, abrupt changes in direction in the piping system: Where structural conditions cause numerous directional changes, long radius (1.5 x diameter) fittings should be used to minimize the interruption of laminar flow.
- Lack of reaming of the tube ends: Burrs left on the interior diameter of the tube can interrupt laminar flow, resulting in localized high water velocity and cavitation. In the area immediately downstream of the unreamed tube ends, the local flow pressure can be drasti-

cally reduced due to the sharp burr in the flow stream. This decrease in local flow pressure allows air bubbles entrained in the water to escape and scour the tube/fitting wall, creating pits that eventually lead to failure.

- Protrusions in the flow stream: These can be caused by excessive lumps of solder/braze material, improperly fabricated tees (branch protruding into the run pipe), etc. These protrusions can also interrupt laminar flow, resulting in localized high water velocity and cavitation.
- Excessive water temperature: Heating the water above 140°F (60°C) can accelerate the process of erosion/corrosion. To avoid "cold" hot water concerns, insulation can be added to the hot water supply lines.
- Excessive amounts of dissolved gases, vapors, or suspended solids in the water conveyed: At high velocities these gases, vapors, or solids can impinge on the metal surface, causing erosion/corrosion.

Short of visual inspection of the interior tube surfaces, there is no sure way to determine if a system is being affected by erosion/corrosion. However, in some cases noise is created in the system, especially in the area of joints, pumps, valves, and components. This noise is generally characterized as sounding like gravel bouncing through the line.

Upon visual examination of interior tube surfaces, areas of severe horseshoe-shaped pitting usually characterize damage due to erosion/corrosion. These pits are generally undercut, with the deepest section of the pit occurring at its upstream end with the horseshoe opening in the direction of flow. In cases where prolonged damage has occurred, distinct horseshoe-shaped pits may no longer be distinguishable, giving way to entire areas of the tube wall that have been worn away. These areas are generally clean, free of corrosion products, and may have a rippled appearance.

Although it is virtually impossible to rehabilitate a piping system that is experiencing erosion/corrosion-related failures, short of replacing joints and affected areas, a number of recommendations can be made to mitigate the erosion/corrosion of copper tube systems. The water flow rates should be measured in the affected sections of the system and, if necessary, reduced to ensure that they do not routinely exceed 5–8 fps in cold water systems and 4–5 fps in hot water systems. References such as the Copper Development Association's *Copper Tube Handbook* provide basic information regarding desirable flow rates.

The water chemistry in the affected system should also be checked for excessive amounts of suspended gases, vapors, and solids. Also, system temperature should be monitored to ensure that temperature spikes are not occurring. As the temperature of the water in the system approaches the boiling point of water, localized areas of low pressure in the piping system may allow the water to flash into steam, greatly increasing the possibility of erosion/corrosion.

Finally, plumbing technicians must use industry standard workmanship when installing copper tube systems. Cut tube ends must be properly reamed/deburred prior to soldering. Adhering to the general guidelines for tube installation, joint preparation, and soldering presented in the *Copper Tube Handbook* and ASTM B828: *Standard Practice for Making Capillary Joints by Soldering of Copper and Copper Alloy Tube and Fittings* should eliminate many of the erosion/corrosion concerns associated with improper workmanship. This condition is not peculiar to copper tube, but can affect other materials as well. However, when erosion/corrosion does occur in copper tube, it is readily identifiable by the distinctive horseshoe-shaped pitting throughout the inside of the tubes.

CORROSION OF MIXED-METAL FIRE SPRINKLER SYSTEMS

The capability of mixed metals specifically to resist galvanic corrosion is sometimes questioned. The concern expressed focuses primarily on composite systems where copper tube branch lines and cross mains are used in connection with steel pipe feed mains, risers, and standpipes. Other areas of concern are the use of steel band or ring hangers to support copper tube, the practice of threading copper tube through steel sleeves for wall penetrations, and the potential for galvanic corrosion between copper tube and metal building studs in interior wall partitions. Frequently, the erroneous assumption is made that copper components corrode preferentially. This is not accurate. Should galvanic corrosion occur, the steel or cast iron components are normally attacked. The protection of the ferrous materials via dielectric separation, protective insulating tape, sleeves, or grommets must be evaluated. The beneficial results achieved versus the attendant increased costs of such protective measures must also be evaluated.

A standard galvanic series (a practical simplification of the electrochemical series of the elements) provides a first approximation of galvanic corrosion potential and is a starting point for understanding the problem. In a standard galvanic series, the common metals are ranked from the most active (anodic) to the least active (cathodic). Generally, when two dissimilar metals are coupled in the presence of an electrolyte (such as water), the potential for accelerated corrosion of the more active metal in the couple increases in proportion to the position of the metals in the standard galvanic series.

Using the standard galvanic series for common metals in seawater (refer back to Table 8-2), aluminum, which is ranked second in activity to magnesium, would exhibit a greater potential for galvanic corrosion when in direct contact with copper, which is ranked in the lower third of the series, than iron (steel), which is ranked in the middle third of the series.

The amount or severity of galvanic corrosion, however, cannot be predicted simply on the basis of the relative ranking of the two metals forming the couple in a standard galvanic series. The rate and extent of corrosion potential also depend on:

- The electrical resistance of the joint between the metals
- The conductivity of the electrolyte
- The relative areas or masses of the anodic metal with respect to the cathodic metal
- The polarization of the anodic metal through the buildup of adherent surface films

Considering each of these factors in the context of an automatic fire sprinkler system, the following can be interpreted:

- Black steel pipe is anodic with respect to copper tube. However, the close proximity of the two metals in the standard galvanic series indicates that the corrosion potential is only moderate.
- Where the transition from copper tube to steel pipe employs a standard gasketed flanged fitting, the electrical resistance of the joint increases, while the potential for corrosion decreases.

The use of threaded transitional fittings of either wrought or cast copper alloy are also appropriate when joining copper tube and steel pipe conductors. The pipe dope or tape sealant, which is normally applied to the threads, tends to increase the joint's electrical resistance, further decreasing the corrosion potential.

In a wet pipe sprinkler system, the standing water condition tends to reduce the aggressive character of the electrolyte (conductivity of the water) as the corrosive elements in the water react with the pipe or tube to form superficial surface films. This is unlike the situation encountered in domestic and process water distribution systems, where intermittent flow tends to replenish the strength of the electrolyte.

In dry pipe sprinkler systems, particularly where positive drainage is not assured, the potential for galvanic corrosion may increase slightly in those portions of the system where water collects in the presence of a copper-steel couple, which acts as a catch basin.

The relative masses of the metals in contact have a significant impact on the galvanic corrosion potential. When the mass of the copper is small in comparison to the mass of the steel, the corrosion potential is relatively low. For example, no special precautions are taken when installing bronze sprinkler heads in either cast iron or malleable iron fittings. Bronze-bodied valves are frequently installed in steel pipe sprinkler systems without exercising special protective measures. In large iron-bodied valves, bronze seats, wedges, and stems are commonly employed.

Since economics tend to dictate the use of smaller-diameter, lighter-weight copper tube branch lines and cross mains in conjunction with steel pipe feed mains and risers, the mass or area of the steel pipe portions of the system tend to be relatively large in comparison to the copper tube portion of the system, thus reducing the potential for significant corrosion.

Polarization of the anodic metal through the buildup of adherent surface films is probably not a factor.

In essence, when all factors are weighed, the potential for significant corrosion of steel pipe in a composite copper/steel pipe fire sprinkler system is relatively low, and the requirement for dielectric separation usually is not warranted, unless the mass of the steel is small in comparison to the mass of the copper and intermittent water flow is permitted within the system, thus replenishing the electrolyte. Routine inspection, testing, and flushing, or other infrequent maintenance that introduces fresh electrolytes into the system, are not a significant factor. The inherent corrosion-resistant properties of the copper metals indicate that system flushing of all-copper systems need not be completed on the same frequency as normally required for the flushing of corrosive scale and rust from all-steel systems.

Copper fire sprinkler systems are frequently concealed within the interior stud wall partitions. When metal building studs are employed, the copper tube is normally threaded through an opening in the web of the metal stud. A common field practice permits the tube to rest on the edge of the web opening, thereby eliminating the need for additional hangers. Since the water within the fire sprinkler system is stagnant, it will assume the ambient temperature found within the wall partition, with the result that condensation will not collect on the outside surface of the copper tube. Without the presence of moisture at the point of contact between the copper tube and the metal building stud, galvanic corrosion should not occur. The requirement for protective insulating sleeves or grommets, or the application of tape or other insulating material at the point of contact, may not be warranted in this instance. Care should be exercised, however, to ensure that the copper tube is not abraded when it is threaded through punched or drilled openings in the metal building stud during installation of the fire sprinkler system.

Similarly, the use of steel band or ring hangers, either plain or cadmium plated, for the support of copper tube and steel sleeves (for wall penetrations) that are in contact with copper tube will normally prove satisfactory, except in those instances where contact surfaces are frequently or continuously moist. Laundries, dye houses, piers, and wharves are a few examples of locations where plain steel hangers should not be employed in conjunction with copper tube. Threading copper tube through steel sleeves for the penetration of foundation walls, or any other wall where the presence of moisture could be expected to occur, are examples of locations where plain steel sleeves should not be employed in conjunction with copper tube unless a suitable insulating material is installed to minimize or prevent the corrosion of the steel component.

Economics and modern building practices and techniques have spurred the rapid growth of copper tube and fitting use in fire sprinkler system installations where copper tube and steel pipe are joined or the two metals are placed in direct contact. No cases of galvanic corrosion in these systems have been reported, and none are anticipated where all factors have been considered and rational judgments made.

While it is acknowledged that a significant galvanic corrosion potential will not occur simply by the contact or joining of copper and steel materials, reasonable care must be exercised in determining the desirability of isolating the contact surfaces for each individual application. A blanket requirement to insulate the contact surfaces would place unnecessary additional costs on the fire sprinkler system installation and in most typical applications would afford negligible additional protection.

MICROBIOLOGICALLY INFLUENCED CORROSION

The deterioration of metallic materials by the activities of various microorganisms (microbes), hereinafter referred to as microbiologically influenced corrosion (MIC), is a ubiquitous problem that occurs in freshwater, brackish water, and seawater environments. MIC can have a wide range of short-term to long-term deleterious effects on water wells; these include, but are not limited to, dramatically reducing the useful life of the water well casing and screen and causing a marked increase in the cost to operate a well due to its effects (i.e., lowered specific capacity, reduced well efficiency, and higher power consumption). MIC can result in pitting, crevice corrosion, selective dealloying, stress corrosion cracking, and underdeposit corrosion.

MIC is an interesting and complex topic that has been the subject of many studies regarding its occurrence, treatment, and effects. Much useful information is available on MIC in a wide variety of professional publications, texts, and on the Internet. The following provides a brief, concise overview of MIC. Those who require a detailed explanation of MIC are encouraged to seek out pertinent information from any of the references listed herein and others.

Table 8-5 Bacteria Known to Cause MIC

Genus of Species	pH	Temperature Range °C	Oxygen Requirement	Metals Affected
Desulfovibrio	4–8	10-40	Anaerobic	Iron, steel, stainless steels, aluminum, zinc, and copper alloys
Desulfotomaculum	6–8	10–40 (some 45–75)	Anaerobic	Iron and steel; stainless steels
Desulfomonas		10–40	Anaerobic	Iron and steel
Thiobacillus thioxidans	0.5–8	10–40	Aerobic	Iron and steel, copper alloys
Thiobacillus ferrooxidans	1–7	10–40	Aerobic	Iron and steel
Gallionella	7–10	20–40	Aerobic	Iron and steel
Sphaerotilus	7–10	20–40	Aerobic	Iron and steel

Source: Modified from D.A. Jones, 1995

Mechanism

MIC occurs as microbes grow and metabolize in either aerobic or anaerobic conditions. Microbes that rely on oxygen are referred to as aerobic; those that can live in environments with little or no oxygen are anaerobic. Table 8-5 presents a brief list of some microbes that are associated with MIC. As microbes go about their existence, they regularly produce gelatinous slimes, metabolites (e.g., organic acids, sulfates, and sulfide) that lead to aggressive environments for metals, and microhabitats suitable for the proliferation of other bacteria species (e.g., sulfate-reducing bacteria). Microbes also participate in corrosive electrochemical reactions that can start or speed up electrode reaction.

MIC affects metallic surfaces in a unique manner. Whereas general corrosion affects an entire surface, MIC is localized. The microbes initiate the process with a search for a suitable place for habitation. They seek out irregularities on the surface of the well casing and/or screen where they can attach themselves. Once in residence, they begin their life-cycle activity and generate by-products such as sticky polymers, which retain various organic and inorganic materials. These by-products are important to the development of rounded to irregularly shaped nodules, and beneath each nodule is a pit. The nodule serves as the habitat for the microbe community. In a typical nodule found in an aerobic environment, microbes live within its exterior layer where they consume oxygen in the water. As they do so, they reduce the oxygen level within the outer layer of the nodule. This activity creates an environment that allows the underlying anaerobic bacteria to survive and thrive. When a nodule is developed, it creates conditions that are chemically dissimilar to the surface material to which it is attached. This is the beginning of accelerated corrosion. As the microbe community continues to live and develop within the nodule, its by-products eventually lower the pH to acidic levels, which in turn increases the corrosive conditions within the underlying crevice on the metallic surface (i.e., well casing and/or screen).

The acidic conditions actually promote the growth and development of other acid-producing bacteria whose own acid by-products further reduce the pH to even lower levels. The continuance of the MIC mechanism eventually leads to the existence of a nodule over a mature pit. At this point, pH may be less than 4, and live bacteria may exist only in the outer layer of the nodule. In fact, the bacteria could be eliminated, yet traditional electrochemical corrosion would continue. Hence, this form of corrosion is referred to as microbiologically "influenced" corrosion.

MIC has the potential to seriously impact the efficiency and structural integrity of water wells. Therefore, it is imperative to correctly diagnose and treat such problems as soon as possible to interrupt and curtail the development process of the microbe community. Many diagnostic and treatment methods are available that can be implemented. Therefore, one must first identify the type of microbial community in the well and then develop an appropriate course of treatment.

CORROSION IN PLASTICS

Plastic materials corrode different than metallic materials. Physicochemical processes rather than electrochemical reactions are responsible for the degradation of plastics. Plastic materials are attacked by swelling, dissolution, and bond (joint) rupture due to chemical reaction (oxidation), heat, and radiation (sunlight). These reactions can occur singly or in combination.

The traditional method of expressing the rate of corrosion as weight loss cannot be used for plastic materials. Other evaluation methods such as change in hardness, tensile properties, losses or gains in dimensions, elongation, and appearance changes determine the corrosion effect on a plastic material. The effects of various environments on plastic materials are tabulated for each specific plastic material as shown in Table 8-6. The designer must evaluate plastic materials against the chemical environment inside and outside of the material.

Table 8-6 Chemical Resistance for Common Plastics[a]

	Pipe Material		
Chemical Name	ABS	PVC	CPVC
Acetone	NR	NR	NR
Beer	120	140	180
Chlorox bleach solution, 5.5%CL2	NR	NR	NR
Citric acid, 10%	160	140	180
Detergents	73	140	NR
Distilled water	160	140	180
Ethylene glycol, up to 50%	170	140	180
Plating solutions, nickel	INC	140	180
Propylene glycol, up to 25%	73	140	180
Seawater	160	140	180
Soaps	160	140	180
Water	160	140	180

NR = Not recommended
INC = Incomplete data
[a] Based on data from Charlotte Pipe and Foundry, *Plastics Technical and Installation Manual,* January 2008

GLOSSARY

Active The state in which a metal is in the process of corroding.

Active potential The capability of a metal corroding based on a transfer of electrical current.

Aeration cell An oxygen concentration cell—an electrolytic cell resulting from differences in the quantity of dissolved oxygen at two points.

Amphoteric corrosion Corrosion usually caused by a chemical reaction resulting from a concentration of alkaline products formed by the electrochemical process. Amphoteric materials are those materials that are subject to attack from both acidic and alkaline environments. Aluminum and lead, commonly used in construction, are subject to amphoteric corrosion in highly alkaline environments. The use of cathodic protection in highly alkaline environments, therefore, intensifies the formation of alkaline by-products.

Anaerobic Free of air or uncombined oxygen.

Anion A negatively charged ion of an electrolyte that migrates toward the anode under the influence of a potential gradient.

Anode Negative in relation to the electrochemical process. The electrode at which oxidation or corrosion occurs.

Anodic protection An appreciable reduction in corrosion by making a metal an anode and maintaining this highly polarized condition with very little current flow.

Cathode Positive in relation to the electrochemical process. The electrode where reduction (and practically no corrosion) occurs.

Cathodic The electrolyte of an electrolytic cell adjacent to the cathode.

Cathodic corrosion An unusual condition in which corrosion is accelerated at the cathode because cathodic reaction creates an alkaline condition corrosive to certain metals, such as aluminum, zinc, and lead.

Cathodic protection Reduction or elimination of corrosion by making the metal a cathode by means of an impressed DC current or attachment to a sacrificial anode.

Cation A positively charged ion of an electrolyte that migrates toward the cathode under the influence of a potential gradient.

Caustic embrittlement Weakening of a metal resulting from contact with an alkaline solution.

Cavitation Formation and sudden collapse of vapor bubbles in a liquid, usually resulting from local low pressures, such as on the trailing edge of an impeller. This condition develops momentary high local pressure, which can mechanically destroy a portion of the surface on which the bubbles collapse.

Cavitation corrosion Corrosion damage resulting from cavitation and corrosion in which metal corrodes and pressure develops from collapse of the cavity and removes the corrosion product, exposing bare metal to repeated corrosion.

Cell A circuit consisting of an anode and a cathode in electrical contact in a solid or liquid electrolyte.

Concentration cell A cell involving an electrolyte and two identical electrodes, with the potential resulting from differences in the chemistry of the environments adjacent to the two electrodes.

Concentration polarization That portion of the polarization of an electrolytic cell produced by concentration changes resulting from passage of electric current through the electrolyte.

Contact corrosion Corrosion of a metal at an area where contact is made with a usually nonmetallic material.

Corrosion Degradation of a metal by chemical or electrochemical reaction with its environment.

Corrosion fatigue Reduction of fatigue durability by a corrosive environment.

Corrosion fatigue limit The maximum repeated stress endured by a metal without failure in a stated number of stress applications under defined conditions of corrosion and stressing.

Corrosion mitigation The reduction of metal loss or damage through use of protective methods and devices.

Corrosion prevention The halting or elimination of metal damage through use of corrosion-resisting materials, protective methods, and protective devices.

Corrosion potential The potential that a corroding metal exhibits under specific conditions of concentration, time, temperature, aeration, velocity, etc.

Couple A cell developed in an electrolyte resulting from electrical contact between two dissimilar metals.

Cracking Separation in a brittle manner along a single or branched path.

Crevice corrosion Localized corrosion resulting from the formation of a concentration cell in a crack formed between a metal and a nonmetal or between two metal surfaces.

Deactivation The process of prior removal of the active corrosion constituents, usually oxygen, from a corrosive liquid by controlled corrosion of expendable metal or by other chemical means.

Dealloying The selective leaching or corrosion of a specific constituent from an alloy.

Decomposition potential (or voltage) The practical minimum potential difference necessary to decompose the electrolyte of a cell at a continuous rate.

Depolarization The elimination or reduction of polarization by physical or chemical means, resulting in increased corrosion.

Deposit attack (deposition corrosion) Pitting corrosion resulting from accumulations on a metal surface that cause concentration cells.

Differential aeration cell An oxygen concentration cell resulting from a potential difference caused by different amounts of oxygen dissolved at two locations.

Drainage Conduction of current (positive electricity) from an underground metallic structure by means of a metallic conductor.

Electrode A metal in contact with an electrolyte that serves as a site where an electrical current enters the metal or leaves the metal to enter the solution.

Electrolyte An ionic conductor (usually in aqueous solution).

Electromotive force series A list of elements arranged according to their standard electrode potentials, the sign being positive for elements having potentials that are cathodic to hydrogen and negative for elements having potentials that are anodic to hydrogen. (This convention of sign, historically and currently used in European literature, has been adopted by the Electrochemical Society and the National Institute of Standards and Technology; it is employed in this publication. The opposite convention of Gilbert N. Lewis has been adopted by the American Chemical Society.)

Electronegative potential A potential corresponding in sign to those of the active or anodic members of the electromotive force series. Because of the existing confusion of sign in the literature, it is suggested that "anodic potential" be used whenever "electronegative potential" is implied. (See *electromotive force series*.)

Electropositive potential A potential corresponding in sign to potentials of the noble or cathodic members of the electromotive force series. It is suggested that "cathodic potential" be used whenever "electropositive potential" is implied. (See *electromotive force series*.)

Flash attack A heavily etched, dark surface resulting from contaminated passivating solutions with high chloride levels.

Forced drainage Drainage applied to underground metallic structures by means of an applied electromotive force or sacrificial anode.

Galvanic cell A cell consisting of two dissimilar conductors in contact with an electrolyte or two singular conductors in contact with dissimilar electrolytes. More generally, a galvanic cell converts energy liberated by a spontaneous chemical reaction directly into electrical energy.

Galvanic corrosion Corrosion that is increased because of the current caused by a galvanic cell (sometimes called couple action).

Galvanic series A list of metals arranged according to their relative corrosion potential in some specific environment; seawater often is used.

General corrosion Corrosion in a uniform manner.

Graphitization (graphitic corrosion) Corrosion of gray cast iron in which the metallic constituents are converted to corrosion products, leaving the graphite flakes intact. Graphitization also is used in a metallurgical sense to mean the decomposition of iron carbide to form iron and graphite.

Hydrogen embrittlement A weakening of a metal by the entrance of hydrogen into the metal through, for example, pickling or cathodic polarization.

Hydrogen overvoltage A higher-than-expected difference in potential associated with the liberation of hydrogen gas.

Impingement attack Localized erosion/corrosion caused by turbulence or impinged flow at certain points.

Inhibitor A substance that, when added in small amounts to water, acid, or other liquids, sharply reduces corrosion.

Ion An electrically charged atom or group of atoms known as radicals.

Microbiologically influenced corrosion (MIC) The deterioration of metallic materials by the activities of various microorganisms (microbes).

Natural drainage Drainage from an underground metallic structure to a more negative structure, such as the negative bus of a trolley substation.

Noble potential A potential substantially cathodic compared to the standard hydrogen potential.

Open-circuit potential The measured potential of a cell during which no significant current flows in the external circuit.

Overvoltage The difference between the potential of an electrode at which a reaction is actively taking place and another electrode is at equilibrium for the same reaction.

Oxidation Loss of electrons, as when a metal goes from the metallic state to the corroded state. Thus, when a metal reacts with oxygen, sulfur, etc. to form a compound as oxide, sulfide, etc., it is oxidized.

Oxygen concentration cell A galvanic cell caused by a difference in oxygen concentration at two points on a metal surface.

Passive The state of a metal when its behavior is much more noble (resists corrosion) than its position in the electromotive force series would predict. This is a surface phenomenon.

pH A measure of the acidity or alkalinity of a solution (from 0 to 14). A value of 7 is neutral; low numbers (0–6) are acidic, large numbers (8–14) are alkaline.

Pitting Localized light corrosion resulting in deep penetration at a small number of points.

Polarization The shift in electrode potential resulting from the effects of current flow, measured with respect to the zero-flow (reversible) potential, i.e., the counter-electromotive force caused by the products formed or concentration changes in the electrode.

Protective potential A term sometimes used in cathodic protection to define the minimum potential required to suppress corrosion. For steel in seawater, this is claimed to be about 0.85 V as measured against a saturated calomel cell.

Remote electrode (remote earth) Any location away from the structure at which the potential gradient of the structure to earth is constant. The potential of a structure-to-earth will change rapidly near the structure, and if remote earth is reached, there will be little or no variation in the voltage.

Resistivity The specific opposition of a material. Measured in ohms (Ω) to the flow of electricity.

Rusting Corrosion of iron or an iron-base alloy to form a reddish-brown product that is primarily hydrated ferric oxide.

Stray current corrosion Corrosion that is caused by stray currents from some external source.

Stress corrosion/stress-accelerated corrosion Corrosion that is accelerated by stress.

Stress corrosion cracking Cracking that results from stress corrosion.

Tuberculation Localized corrosion at scattered locations resulting in knob-like mounds.

Under-film corrosion Corrosion that occurs under lacquers and similar organic films in the form of randomly distributed hairlines (most common) or spots.

Weld decay Corrosion, notably at specific zones away from a weld.

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Expiration date: Continuing education credit will be given for this examination through **February 28, 2019**.

CE Questions — "Corrosion" (CEU 256)

Test written by Yasser Amer Ahmed, LEED AP BD+C, CPD, CFPS

1. Dissimilar metals, when coupled together in a suitable environment, will corrode according to ________.
   a. Ohm's law
   b. Darcy-Weisbach equation
   c. the temperature of the environment
   d. Faraday's law

2. Localized breakdown of protective or layer of corrosion products can cause which type of corrosion?
   a. pitting
   b. uniform
   c. galvanic
   d. crevice

3. The corrosive destruction of one element of an alloy is called ________.
   a. concentration cell attack
   b. stress corrosion cracking
   c. selective attack
   d. impingement attack

4. Which of the following metals is generally anodic to tin?
   a. Type 304 stainless steel
   b. active nickel
   c. lead
   d. none of the above

5. The corrosion of metals in an aqueous solution can be governed by ________.
   a. acidity
   b. oxygen content
   c. temperature
   d. all of the above

6. The rate of corrosion in domestic hot water systems is doubled for each ________ rise above 140°F water temperature.
   a. 5°F
   b. 10°F
   c. 15°F
   d. 20°F

7. ________ is the most common method to prevent corrosion.
   a. coating
   b. cathodic protection
   c. passivation
   d. materials selection

8. In cathodic protection, ________ anodes sometimes are used in very low-resistivity soils.
   a. zinc
   b. nickel
   c. aluminum
   d. magnesium

9. Why are galvanic anodes considered advantageous?
   a. the installation cost is relatively low
   b. the driving voltage is low
   c. no external power source is required
   d. both a and c

10. Which of the following is considered a disadvantage of impressed current cathodic protection?
    a. large current output
    b. power costs
    c. voltage adjustment
    d. both a and c

11. When an alkaline solution contacts a metal causing metal weakening, this is defined as ________.
    a. amphoteric corrosion
    b. hydrogen embrittlement
    c. caustic embrittlement
    d. stray current corrosion

12. The minimum potential required to suppress corrosion is ________.
    a. electropositive potential
    b. electronegative potential
    c. corrosion potential
    d. protective potential