

Manual of Water Supply Practices

**M27**

# External Corrosion Control for Infrastructure Sustainability

Third Edition



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Manual of Water Supply Practices — M27, Third Edition

## External Corrosion Control for Infrastructure Sustainability

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# Preface

Corrosion control is a practical science that allows relatively reliable predictions of corrosive conditions and, more importantly, effective prevention or mitigation strategies to control corrosion where economically appropriate. Faced with how best to install and protect a transmission or distribution system to minimize corrosion, today's water utility manager must compare the cost of implementing reliable corrosion protection with the benefit of ensuring an extended life for pipelines and appurtenances.

Both the technology and the economics involved in external corrosion control are complex, requiring a logical and well-considered approach by utility managers, operators, and consulting engineers, all of whom must be familiar with local conditions and available options. Not all environments are corrosive, not all materials corrode, and there is no single answer to all corrosion problems. In any given situation, the corrective measure selected must be at once the most appropriate for the material and environment involved and economically feasible.

This manual is addressed primarily to the professional water utility operator, whose objective is to provide safe drinking water to the public. The title has been revised for the third edition to reflect the basic premise that corrosion control is an attempt to extend the useful life of water infrastructure. The text is intended to give the reader an understanding of how and why corrosion occurs, how the corrosion potential of an environment is evaluated, and how many of the proven corrosion prevention and control measures operate. For readers who believe a review of theoretical concepts of basic chemistry and basic electrical circuit theory is necessary beyond that which is addressed herein, the relevant sections of *Basic Science Concepts and Applications*\* are recommended.

Updates in this third edition were made to the figures, tables, and text, including discussion of the effects of chemical environment on pipe materials, pitting and crevice corrosion, common water pipe coatings, and recommended protective methods for specific pipe materials. Topics added or expanded on include stray current corrosion, microbiologically induced corrosion (MIC), oxygen-concentration cells, crevice corrosion of stainless steel, galvanic corrosion, and stainless steel in aboveground environments. New emphasis was placed on using field and lab measurements to determine corrosive conditions.

The general principles and examples presented in this manual are not intended to replace the services of a knowledgeable corrosion engineer. However, methodical application of the principles introduced—i.e., determining the cause of corrosion, analyzing its extent, and considering appropriate procedures for prevention or mitigation—will lay the foundation for an effective corrosion control program that will benefit the public and the utility alike.

In the selection and application of corrosion monitoring, protection, and mitigation materials, the operator must confirm that materials in contact with the water supply have been tested and certified in accordance with the standards and regulations relevant to the water utility involved.

---

\**Basic Science Concepts and Applications*, 3rd ed., American Water Works Association, Denver, Colorado (2010), ISBN 9781583217788.

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Chapter **1**

# Importance of Controlling External Corrosion

Corrosion is the deterioration of a material or its properties because of a reaction with its environment. Deterioration of pipelines, valves, pumps, and associated equipment due to external corrosion is an important concern for many water utilities. At one time, corrosion was accepted as inevitable in many soils, and extra thickness for metal piping was often specified to extend the piping's useful life. Today, a variety of techniques are available to eliminate or significantly reduce external corrosion. Determining the need for such corrosion-control measures and selecting the most appropriate techniques are the primary topics of this manual. *Corrosion* is generally defined as deterioration of a metal or an alloy by reaction with its environment. For the purposes of this manual, corrosion also includes the dissolving of other water system materials through contact with water or soil.

This chapter first presents a brief introduction to the science and terminology of corrosion and then discusses economic implications and managerial responsibility for external corrosion-control programs.

After completing this chapter, the reader should be able to

- Define corrosion.
- Recognize certain environmental conditions and items of water supply equipment that are often associated with external corrosion problems.
- Understand the cost to remedy and the extent of the corrosion problem.
- Recognize potential hazards to public health and safety that may result from corrosion.

- Understand the basic economic questions that must be asked when selecting measures for corrosion control.
- Recognize the responsibilities for a corrosion-control effort that must be assumed by various utility personnel.

## CORROSION: OCCURRENCE AND IMPLICATIONS

Corrosion is a natural phenomenon. Metals are normally found in their stable, oxidized (corroded) form in nature. Iron ores, for example, are found as iron oxides. These oxides are chemically reduced in the refining process to produce useful metal, with the iron atoms in the elemental (unoxidized) form. In the presence of oxygen and water, or under certain soil and electrical conditions, refined iron tends to return to its more stable form, iron oxide (rust). Some waters and some soils are especially favorable to corrosion. The US Federal Highway Administration (FHWA 2002) performed a two-year study on the direct costs associated with metallic corrosion in nearly every US industry sector, from infrastructure and transportation to production and manufacturing. The study provides current cost estimates and identifies national strategies to minimize the effect of corrosion. Results of the study show that the total annual estimated direct cost of corrosion in the United States is \$276 billion (\$36 billion for drinking water and sewer systems).

### Potentially Corrosive Conditions

Several conditions increase the likelihood that corrosion will occur in a water utility system:

- Dissimilar metals or alloys in contact with each other and with a common media, such as water or soil.
- Great variances in soil in contact with metal or alloys.
- Naturally occurring corrosive soil.
- Atmospheric corrosion.
- Environmental contamination of soil with chemical waste, cinders, mine wastes, salts, or other refuse.
- Stray current corrosion, including exposure to stray direct-current earth currents from transit systems.
- Microbiologically influenced corrosion.

These conditions, discussed briefly in the following sections, are examined in detail in chapters 2 through 4 of this manual. Where such conditions occur, the water utility staff should be especially alert to the selection of materials and preventive measures that will minimize the effects of corrosion.

**Dissimilar metals.** Iron and copper are among the metals used in water system piping, valves, pumps, and other equipment. For each application, the manufacturer selects a metal with appropriate properties. There is no single ideal metal or alloy that can satisfy the many requirements of water system equipment.

Unfortunately, whenever two dissimilar metals are immersed in a common corrosive medium (soil or water) and then placed in contact with each other, the likelihood of corrosion significantly increases. The extent of corrosion depends on the characteristics of the corrosive medium and the metals involved. Figures 1-1 through 1-3 illustrate common

uses of dissimilar metals and alloys in water systems. Each of these situations, among many others, poses a potential condition for corrosion.

**Soil variances.** The composition of soil can vary from point to point and with changing soil depth. In many cases, a single metallic unit (pipe, well casing, valve, etc.) may be in contact with two or more completely different soil types. Whenever this situation occurs, the likelihood of corrosion increases. The severity of the corrosion will depend on the soils and the metal involved.

**Naturally corrosive soils.** As noted, some soils tend to promote corrosion. As a general rule, swamps, bogs, peat, and soils with high salt content are corrosive. Low, poorly drained soils are more likely to be corrosive than soils in well-drained areas. The corrosivity (also called *aggressiveness*) of a given soil can be determined by sampling, testing, and analysis.

**Atmospheric corrosion.** Equipment and facilities may experience corrosion due to exposure to the atmosphere, brought on by acid rain, salt spray, industrial chemicals, and other factors.

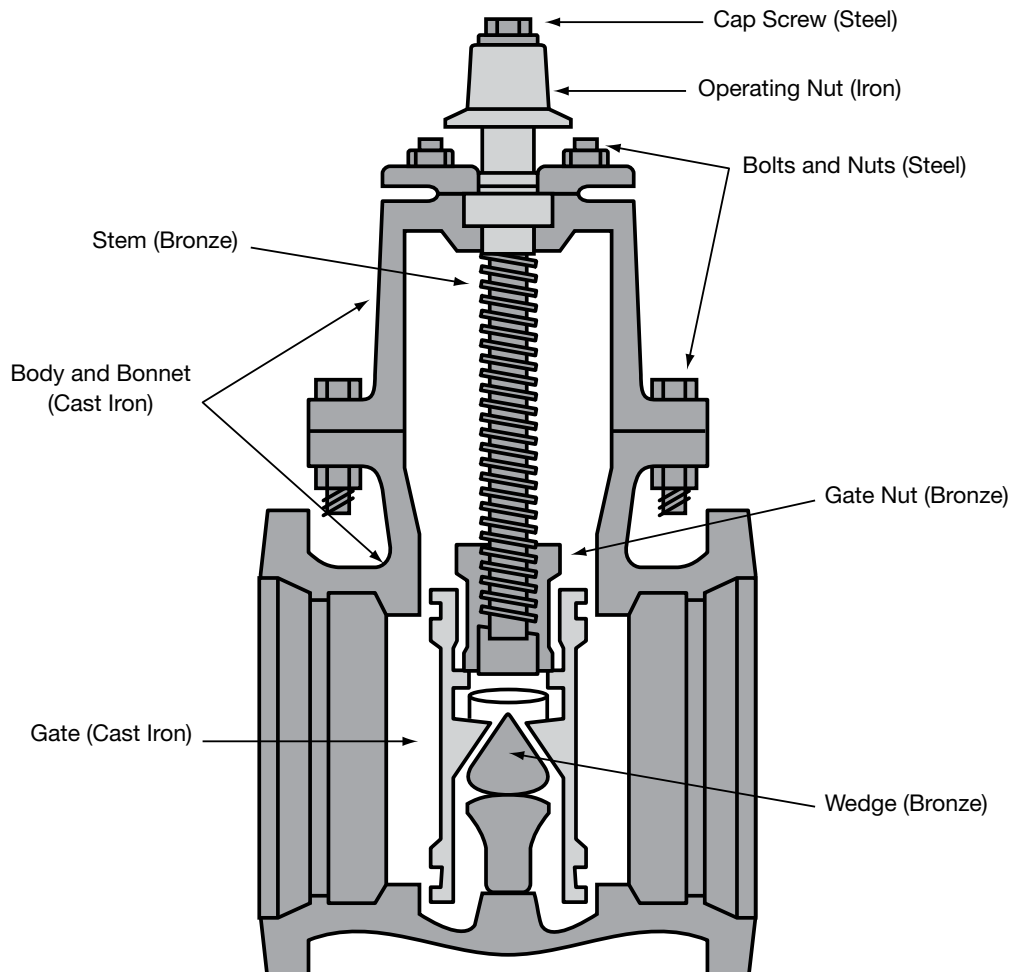


Figure 1-1 Metals used in a typical gate valve

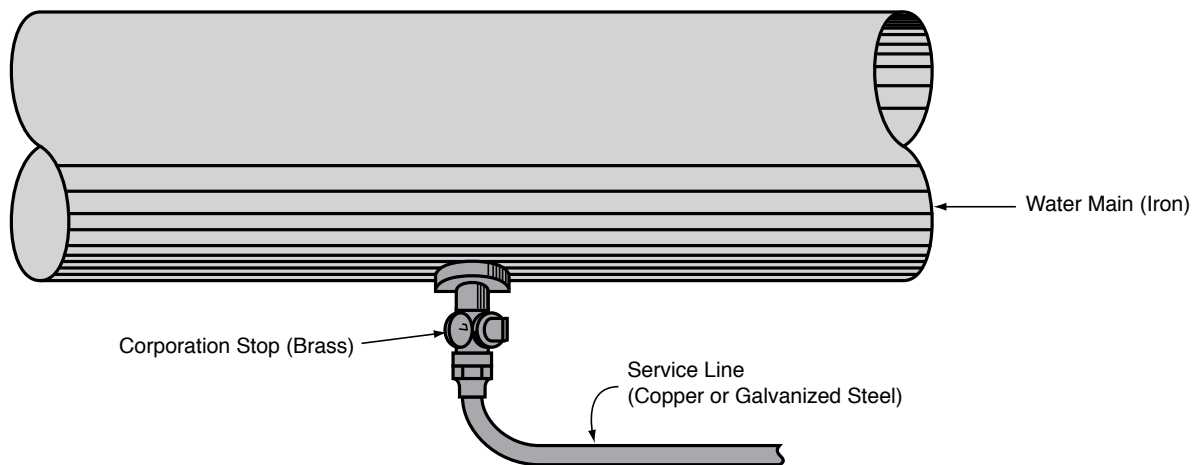


Figure 1-2 Metals used at a typical water-service-to-main connection

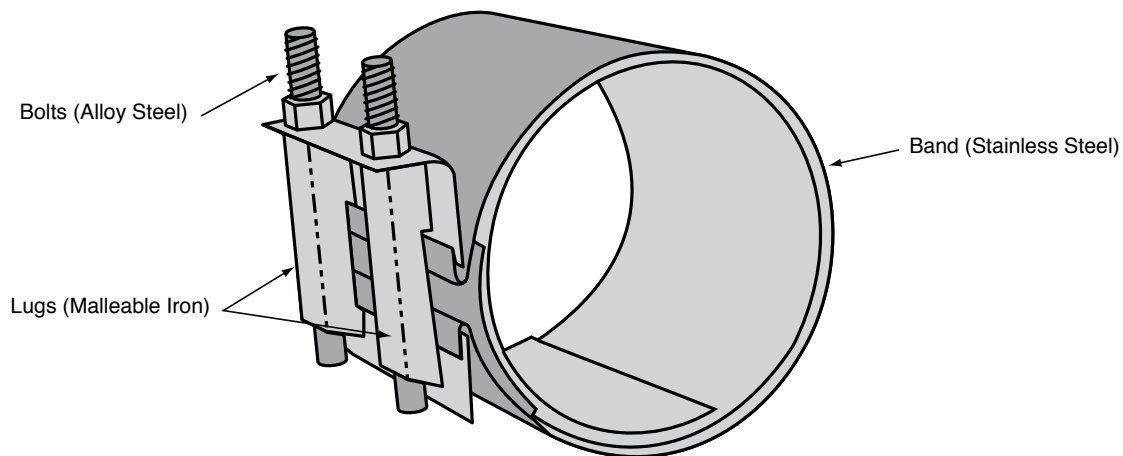


Figure 1-3 Metals used in a pipe-repair clamp

**Environmental contamination.** In many urban areas, the history of street surfacing may offer clues concerning potential corrosion of underground water system materials. Older streets were often surfaced with cinders and later paved. Cinders are aggressive to most pipe and valve materials, and their presence is a warning that serious corrosion may occur.

Coal bottom ash has been used as an aggregate material in flowable fill mixes. Bottom ash (and boiler slag) is composed principally of silica, alumina, and iron, with smaller percentages of calcium, magnesium, sulfates, and other compounds. The composition of

the bottom ash or boiler slag particles is controlled primarily by the source of the coal and not by the type of furnace. Due to the salt content and, in some cases, the low pH of bottom ash and boiler slag, these materials could exhibit corrosive properties. When using bottom ash or boiler slag in an embankment, backfill, subbase, or pipe base course, the potential for corrosion of metal that may come in contact with the material is of concern and should be investigated prior to use.

The presence of chloride salts can create corrosive soils. Steel reinforcement in concrete, iron, copper, brass, and many other materials in common use may be subject to attack if elevated concentrations of chlorides are present in the environment. Heavy use of deicing salts and chemicals on streets and highways can also be a potential source of corrosion.

Finally, sites where chemical contamination has occurred, such as refuse dumps, landfills, and mine or industrial waste disposal areas, may cause deterioration of water utility materials. Such locations should be avoided if possible. However, if alternative locations are not feasible, the potential for corrosion must be considered.

**Stray current corrosion.** [ASTM G15](#), Standard Terminology Relating to Corrosion and Corrosion Testing, defines *stray current corrosion* as “corrosion caused by electric current from a source external to the intended electrical circuit, for example, extraneous current in the earth.” Although stray current corrosion may sometimes be caused by alternating current in areas with a very high alternating-current density, it is normally associated with direct current.

Stray current corrosion is normally localized and will occur at locations on the structure where the direct current is discharged back into the earth. In areas of stray current influences, electrically continuous pipelines accumulate a greater magnitude of stray current flow than electrically discontinuous pipelines. Sources of stray direct current normally include cathodic protection systems, direct (DC) powered streetcars or trains, welding equipment, and mine/industrial equipment.

A more detailed discussion of stray current corrosion is given in chapter 3 (Evaluating the Potential for Corrosion).

**Microbiologically influenced corrosion (MIC).** [ASTM G15](#) defined *microbiologically influenced corrosion* as “corrosion inhibited or accelerated by the presence or activity, or both, of microorganisms.” MIC-related corrosion normally takes the form of pitting, as compared with generalized corrosion. Four primary forms and mechanisms of MIC have been proposed and published (Pope and Morris 1995).

1. One is in instances where a biofilm, a film composed of families of low-nutrient bacteria, forms on the metal surface, creating a differential aeration cell.
2. Another occurs when various mutually beneficial bacteria create a colony housed in a biodome, thereby setting up a corrosion cell by cathodic depolarization.
3. Still another condition may exist in which the biological waste material from these bacteria within the biodome presents a strong acid concentration, which can rapidly perforate the metal substrate.
4. Lastly, conditions can occur that provide for iron-reducing bacteria to flourish. In this instance, bacteria that respire iron (Fe), or utilize Fe in their electron receptor for energy, become citizens of the colony represented in a particular biodome.

To date, there is no widely accepted field method without laboratory analysis to positively identify MIC responsible for, or contributing to, corrosion. MIC continues to be studied and defined to develop reliable field test methods and also to allow more definitive control mechanisms to be developed. A more detailed discussion on MIC is given in chapter 3.

## Implications of Corrosion

Aside from the 2002 FHWA report, information is limited that details costs incurred by the public water supply industry due to corrosion-produced losses. Given the extent and wide variety of materials used in water systems, the amount is certainly substantial.

In addition to the financial impact of repair, replacement, labor, and equipment, other more important costs impact the public as a result of corrosion. The health of water consumers may be threatened whenever extensive corrosion breaches the sanitary integrity of the water system. The ever-present danger of backflow of contaminated liquid into the drinking water system is further increased when water pressure is interrupted to facilitate repairs on corroded wells, pumps, treatment equipment, pipes, valves, and services.

Another concern is that public safety depends heavily on an adequate supply of pressurized water for fire control. Low pressures and insufficient water can result in the growth of small fires into disasters that cause injury, death, and destruction of property. Uncontrolled corrosion can be a major contributor to the problems of unreliable or inadequate fire-control systems.

Controlling corrosion in water utility systems can contribute greatly to cost savings, public health protection, and public safety.

## ECONOMICS OF CORROSION CONTROL

Two primary considerations are involved in any decision regarding corrosion control. The first and more important is the protection of public health and safety. The second is economics. Both private and governmental utilities must operate effectively and efficiently.

In either case, faced with decisions regarding the best corrosion-control programs to implement, water utility staff must determine which actions will produce the lowest overall cost and the highest return on capital. The staff must decide which alternative is preferable: (1) minimize initial costs and accept higher maintenance costs and shorter equipment life or (2) marginally increase initial investment by specifying corrosion-control procedures that will reduce maintenance and extend the life of components.

Economic evaluations are commonly the province of the design engineer and utility management. Determining a reasonable estimate for the anticipated life of alternative installations requires considerable engineering expertise and experience. However, much of the required data is empirical and depends on knowledge of the system and local environmental conditions.

## REFERENCES

- US Federal Highway Administration (FHWA), Office of Infrastructure Research and Development. 2002. *Corrosion Costs and Preventive Strategies in the United States*. Report FHWA-RD-01-156 from CC Technologies Laboratories Inc. <http://www.nace.org/uploadedFiles/Publications/ccsupp.pdf> (accessed July 2013).
- Pope, D.H., and E.A. Morris. 1995. Some Experiences with Microbiologically Influenced Corrosion of Pipelines. *Materials Performance*, 34 (5): 24.

Chapter **2**

# Chemistry of Corrosion

Corrosion in water utility components affects a large number of materials, occurs under a wide range of environmental conditions, and can have greatly varying effects. Nonetheless, the physical mechanisms underlying corrosion are essentially unchanged from one situation to another. In this chapter, basic chemical and electrical reactions of corrosion are explained, and several water utility system configurations where corrosion commonly occurs are described.

After completing this chapter, the reader should be able to

- Explain the basic corrosion reactions.
- Recognize an anode and a cathode on a corroded piece of equipment.
- Explain the difference between a galvanic corrosion cell and an electrolytic corrosion cell.
- Determine which metal will corrode in a bimetal couple.
- Understand how polarization and passivation can retard corrosion.
- Recognize several common types of corrosion and understand why they occur.

## BASIC ELECTROCHEMISTRY OF CORROSION

Corrosion of metals and their alloys is an electrochemical process; that is, a corrosion reaction involves both chemical reactions and the flow of electrons. Two basic types of corrosion occur in a water system: galvanic corrosion and electrolytic corrosion. This section discusses the basic physical configurations and chemistry of each type.

## Galvanic Corrosion

The galvanic corrosion process is identical to the reactions in an electrical battery, in which electrical current is generated by immersing two dissimilar metals, called *electrodes*, in a chemical solution (electrolyte) and connecting them with an external conducting wire, referred to as the *electronic path*. Figure 2-1 shows the elements of a galvanic corrosion cell. Note the solid arrows indicating the direction of electron movement and the black/gray arrows indicating positive current flow. Numerous figures throughout the document illustrate corrosion cells of various types. Most of these show electron flow as “e<sup>-</sup>.” Current flow through the electrolyte is by ion transport and not electron flow. Free electrons do not exist in the electrolyte.

In the galvanic cell, corrosion takes place at the surface of the electrode where electrons are generated to travel through the metal path. This electrode is called the *anode*. The conducting solution (water, soil, or some other chemical solution) is called the *electrolyte*. The electrode to which electrons flow is called the *cathode*. These four elements—the anode, cathode, electrolyte, and electronic path—must exist before corrosion can occur.

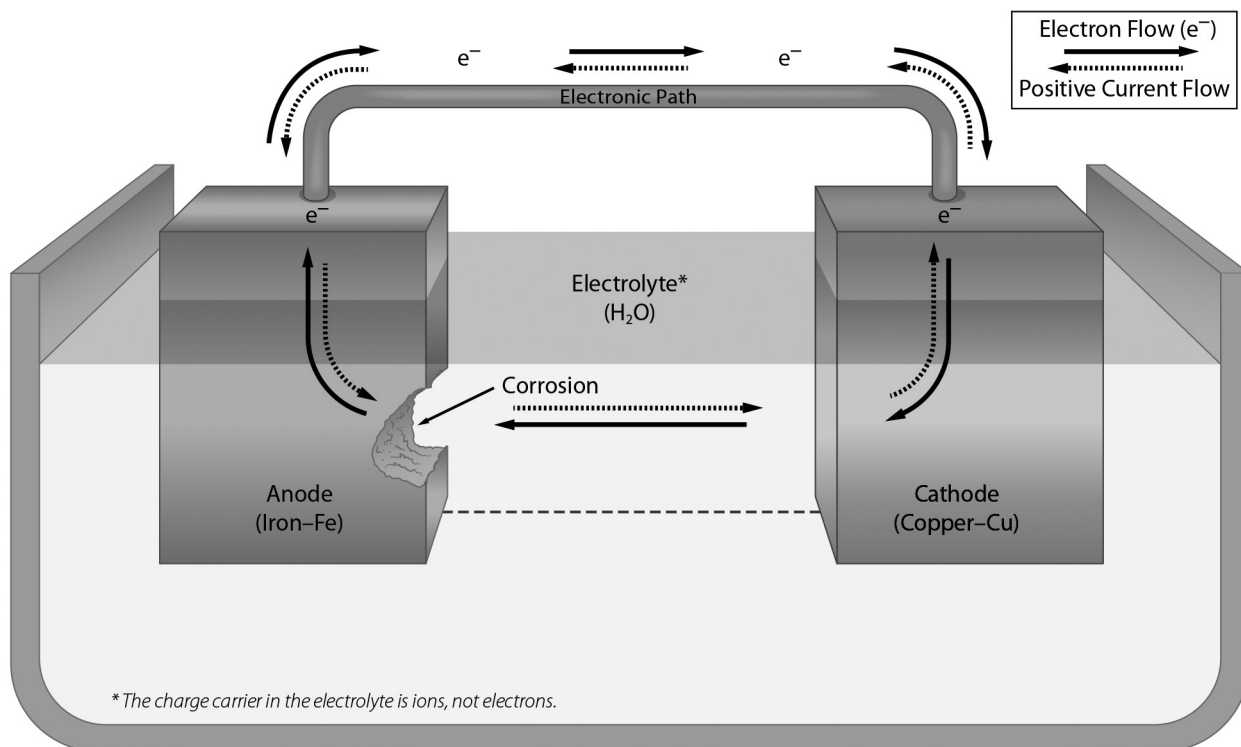


Figure courtesy of NACE International.

**Figure 2-1** The four basic elements of a galvanic corrosion cell: anode, cathode, electrolyte, and electronic path

**Chemistry.** The basic electrochemical reactions occurring in a galvanic corrosion cell are fairly simple. In the cell shown in Figure 2-2, the iron (Fe) anode on the left is corroding. Some of the iron atoms release electrons, which travel across the electronic path and enter the cathode. This loss of electrons changes the iron atoms from elemental iron ( $\text{Fe}^0$ ) to ferrous iron ( $\text{Fe}^{2+}$ ) and then to ferric iron ( $\text{Fe}^{3+}$ ), leaving them with a strong positive charge. Some of the molecules of the electrolyte, in this case pure water ( $\text{H}_2\text{O}$ ), are naturally separated into hydrogen ions ( $\text{H}^+$ ) with positive charges and hydroxyl ions ( $\text{OH}^-$ ) with negative charges. The positively charged iron atoms are attracted to the negative  $\text{OH}^-$  ions. The attraction causes the iron atoms to leave the anode and enter the electrolyte, where they combine with  $\text{OH}^-$  ions. As atoms are lost, the metal surface of the anode deteriorates. This deterioration is corrosion. Note that the products of corrosion,  $\text{Fe}(\text{OH})_2$  and  $\text{Fe}(\text{OH})_3$ , may accumulate on or near the corroded surface.

At the cathode, the negatively charged electrons arrive from the metallic path. The electrons are attracted to the positively charged  $\text{H}^+$  ions in the electrolyte. The attraction causes the electrons to leave the cathode and combine with the  $\text{H}^+$  ions, forming hydrogen gas ( $\text{H}_2$ ). The gas may accumulate on the surface of the cathode. Note that the metal of the cathode does not corrode. In fact, the reactions within the corrosion cell actually protect the cathode from corrosion. This fact forms the basis for cathodic protection (chapter 4).

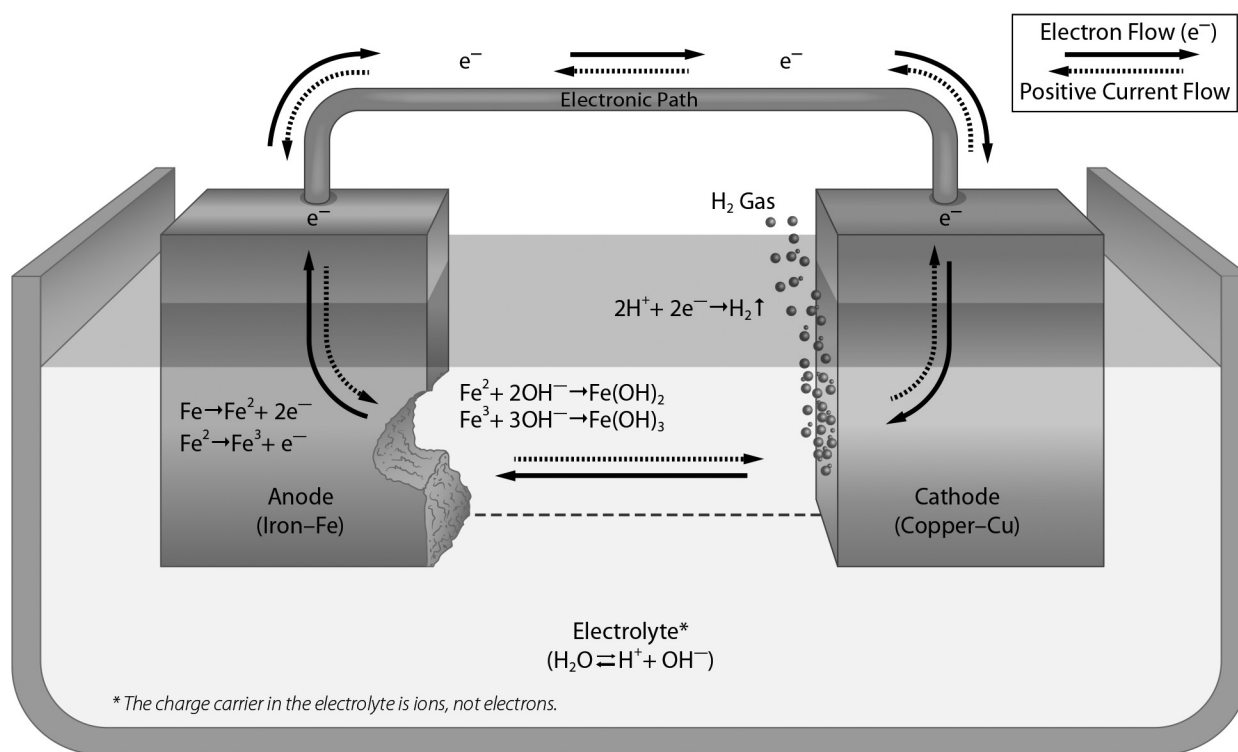


Figure courtesy of NACE International.

**Figure 2-2** Chemical reactions in a typical galvanic corrosion cell

When different materials are used for the electrodes and electrolyte, the chemical reactions will be slightly different. For example, under field conditions, the water forming the electrolyte of the corrosion cell may contain dissolved oxygen. If dissolved oxygen is added to the water in the corrosion cell just described, the reaction at the cathode will combine the oxygen, water, and electrons to yield hydroxyl ions ( $\text{OH}^-$ ) instead of hydrogen gas. Oxygen can react with the surface layer of hydrogen, thereby removing it as a depolarizing agent. Because the layer of hydrogen forms a coating of sorts, and behaves as a resistor, its removal accelerates the cathodic reaction and corrosion activity. Changing the chemical composition of the electrolyte or the materials acting as the electrodes in a corrosion cell can cause great variations in the severity of the corrosion. However, no matter what materials are involved, it will always be the anode that corrodes and sends electrons into the electronic path, and it will always be the cathode that is protected from corrosion.

**Nonuniform electrolytes.** The type of galvanic cell just described has two different metals immersed in a single, uniform electrolyte. A second type of galvanic cell occurs when two pieces of the same metal are immersed in an electrolyte of uneven composition, as shown in Figure 2-3. Because of the uneven nature of the electrolyte, a corrosion cell can develop. One piece of metal will become the anode—it will corrode and feed electrons into the electronic path. The other piece of metal acts as the cathode—it will be protected from corrosion and will feed ionic charge carriers into the electrolyte.

As illustrated in Figure 2-4, the cell just described can be modified so that a single piece of metal acts as the anode, cathode, and electronic path. Figure 2-4A shows the same configuration as Figure 2-3—two electrodes of the same metal in a nonuniform

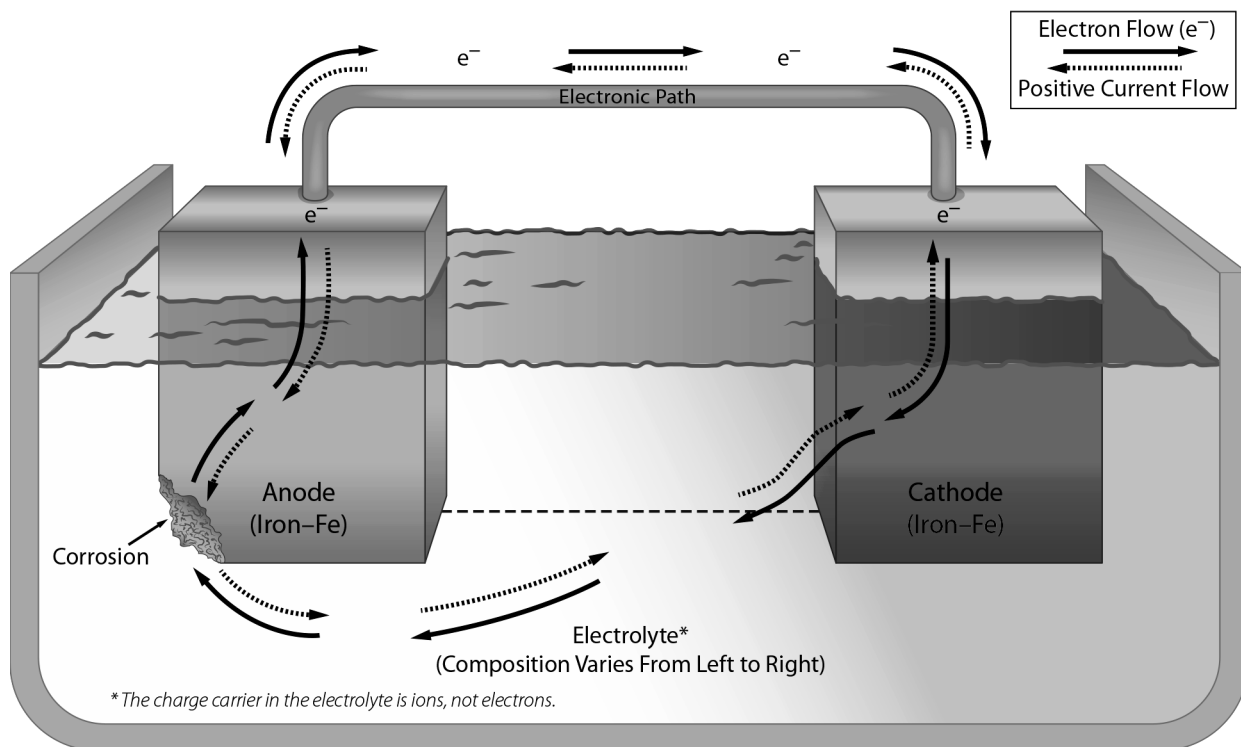


Figure courtesy of NACE International.

**Figure 2-3 Galvanic cell formed with nonuniform electrolyte and electrodes of a single metal**

electrolyte. In Figure 2-4B, the two electrodes have been placed in direct contact with each other, eliminating the connecting wire. In Figure 2-4C, the two separate electrodes have been replaced by a single block of metal, which has one area acting as a cathode, another as an anode, with electrons flowing through the block. In Figure 2-4D, the block of metal, which could be a piece of pipe, has been totally buried in the heterogeneous electrolyte, which could be soil. However, the effect remains the same as in the original configuration—the metal loss occurs at the anode.

Because soil is often nonuniform, a possibility always exists that such corrosion cells can develop around underground metal structures. Whether the cell causes significant damage depends on the corrosivity of the soil as an electrolyte and the type of metal or alloy involved.

**Current flow.** Up to this point, the operation of the galvanic corrosion cell has been described in terms of the movement of electrons. In practice, corrosion cell chemistry is often discussed in terms of electrical current flow, also called *conventional* or *positive current flow*. Because of a historical misunderstanding about the nature of electricity, this conventional current flow is considered to move in the direction opposite to the movement of the electrons. Thus, where electrons leave iron atoms in the anode to travel into the electronic path, the conventional current flow is said to go in the other direction, leaving the surface of the anode and entering the electrolyte. At the cathode, the conventional current flows from the electrolyte into the cathode.

Restated in terms of conventional current flow, the basic galvanic corrosion reaction is as follows (Figure 2-5): electrical current is generated by immersing dissimilar metals

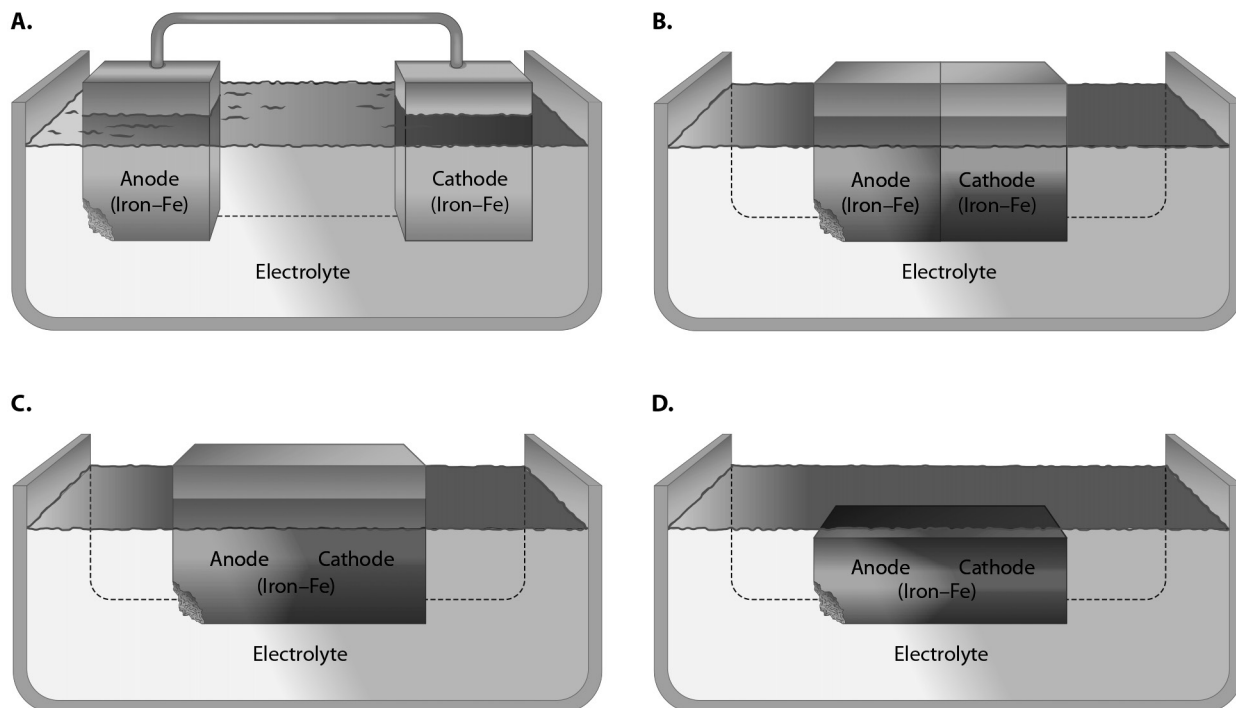


Figure courtesy of NACE International.

**Figure 2-4** Creating a galvanic cell with a single piece of metal in a nonuniform electrolyte

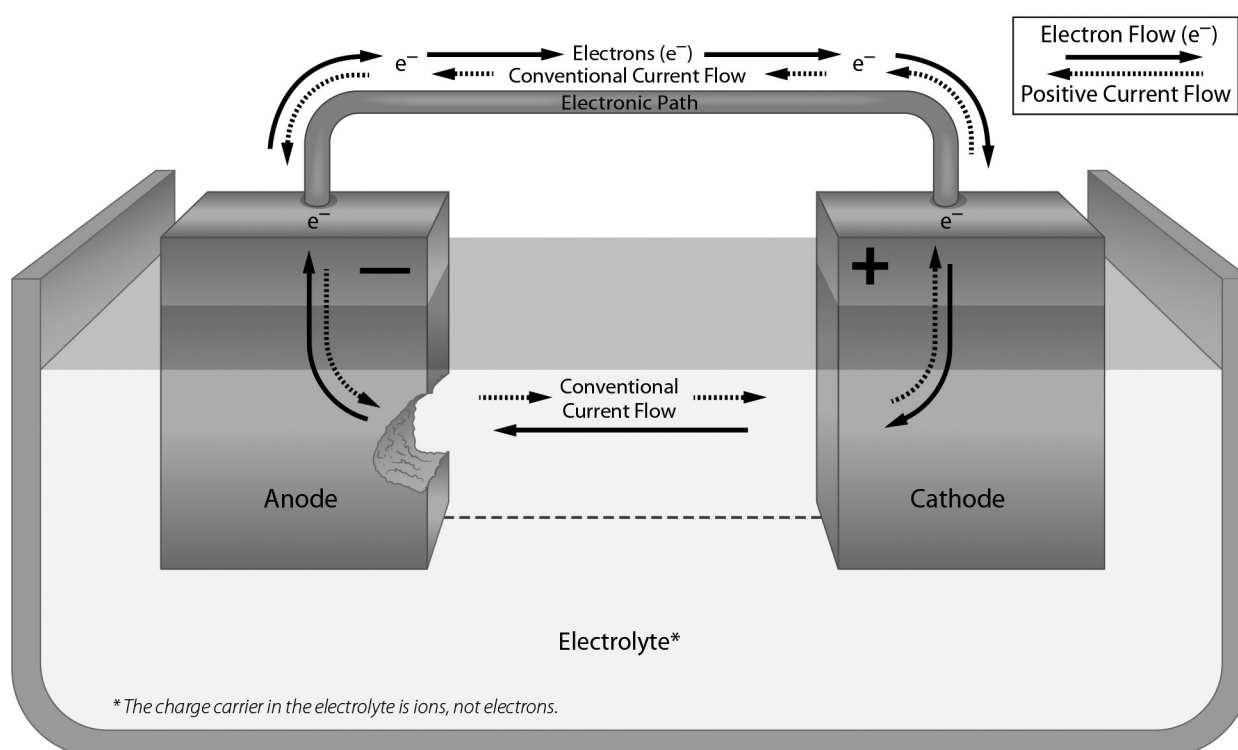


Figure courtesy of NACE International.

**Figure 2-5** Contrasting conventional current flow with electron movement in a galvanic corrosion cell. Current flow in the electrolyte is by ion transport

or alloys in a uniform electrolyte or by immersing a single metal or alloy in a nonuniform electrolyte. The current travels from the anode through the electrolyte to the cathode and returns through the electronic path. At the location of current discharge from the anode into the electrolyte, a loss of anode metal occurs. This loss of metal is corrosion. Corrosion control is the process of reducing, eliminating, or reversing the current flow, thus reducing or eliminating the corrosion.

### Electrolytic Corrosion

The galvanic corrosion cell discussed in the previous section requires an anode, a cathode, an electrolyte, and an electronic path.\* The reactions in the cell generate an electrical current. The configuration of an electrolytic cell is similar to a galvanic cell, but the electrolytic cell does not generate an electrical current. Instead, the corrosion reaction is

\*The committee considered changing the terminology used in the first two editions of this manual from *return current path* to *metal path* or *electronic path*. In the corrosion community and NACE publications, *metal path* is the common term. *Metal path* is not exactly correct because current can also be carried by semiconductors, soil, graphite (carbon) in iron, and graphite or carbon electrodes used by CP systems. Some soils are rectifying and can change AC to DC based on their ability to conduct more efficiently in one direction of current flow than the other. The soils in this case behave as a semiconductor diode. Carbon is not a metal but conducts electricity, including electrons related to corrosion concerns, very well. Another example of a nonmetallic current path is *stray current corrosion*, which occurs when current flows from a source through the soil to an underground structure and that structure sustains damage at the location where the current exits to return to its source. In this scenario, no metal path connects the current source to or from the damaged structure. This is all to say the *return current path* is more descriptive and accurate than *metal path*. After much discussion, *return current path* was changed to *electronic path* as the preferred wording in all occurrences in M27.

driven by a direct-current source originating outside the cell. However, the end result is the same—corrosion at the anode.

Figure 2-6 shows an electrolytic corrosion cell. The four basic elements of the galvanic cell are still necessary: anode, cathode, electrolyte, and electronic path. In addition, an outside direct-current source, located within the electronic path, must exist to drive the reaction. As current is forced through the corrosion cell by the outside current source, corrosion occurs at the anode.

When electrolytic corrosion develops in metals exposed to soil or water, it can be severely damaging. Several situations may arise in which the external direct current needed to drive electrolytic corrosion can occur in the area of a water distribution system. Direct-current-driven train or subway systems can be a source of stray current if the rails (the system's intended electronic path) are not completely electrically isolated from the soil (Figure 2-7). If underground pipe or other metallic equipment picks up a portion of this current, it will corrode at the point where the current ultimately leaves to rejoin the original circuit. Other sources of stray direct current are electric welding equipment grounded to underground utilities and stray direct current from nearby cathodic protection systems.

Alternating current does not have the same magnitude of effect on metal at the point of discharge as direct current and generally does not cause corrosion. In some cases, alternating current at very high current densities can cause corrosion.

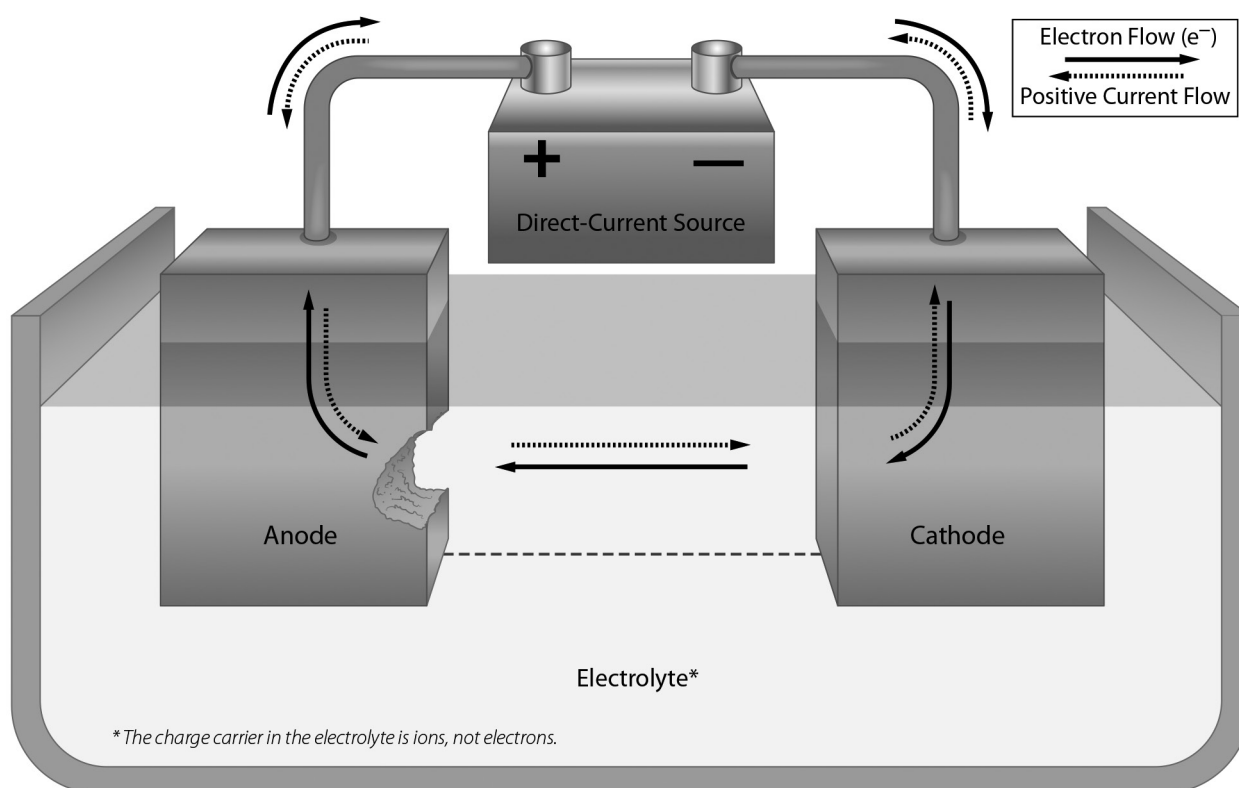


Figure courtesy of NACE International.

**Figure 2-6** A typical electrolytic corrosion cell

## CHEMISTRY OF CORROSION IN WATER SYSTEMS

All corrosion can ultimately be explained in terms of the principles discussed in the earlier sections of this chapter. However, the nature and severity of corrosion within a water system will vary greatly depending on the materials involved, the electrolyte, the physical configuration of the cell, and the environment. This section discusses the calculation of corrosion rates and considers the effects of different materials that may be involved in a galvanic cell. It also explains two physical/chemical processes that may reduce the severity of corrosion and briefly describes a number of common corrosion configurations found in water systems.

### Calculating Corrosion Rate

Corrosion reactions occur in accordance with well-understood physical laws. By determining the conditions surrounding a corrosion cell, the theoretical rate of corrosion can be predicted. Actual field conditions will vary the calculated rate somewhat, but predictions are still an important tool in determining the need for corrosion-control measures.

**Cell voltage.** The chemical reactions occurring in a galvanic corrosion cell force electrons through an electronic path. When the electronic path is disconnected, the force—the potential for current flow—still exists, exhibited as the difference between the electrical charges of the anode and the cathode. As in any electrical circuit, this electrical force is known as *potential*, or *voltage*. The voltage across the electrodes of a galvanic cell that is not connected to an electronic path is called the *cell voltage*, *cell potential*, or *voltage differential*. Voltage is a *relative* measure of driving force for corrosion between two electrodes. It can be measured by connecting the leads of a voltmeter to the two electrodes, as shown in Figure 2-8.

The chemical reactions within a galvanic corrosion cell will vary depending on the materials and electrolyte that comprise the cell, and the cell voltage will vary accordingly. For corrosion cells created as part of a battery designed to generate electrical current, the potential can be several volts. For corrosion cells commonly occurring in water utility piping systems, the voltage will usually be less than 1 V, and it is commonly measured in millivolts (1,000 mV = 1 V). The cell voltage is the driving force that pushes the electrons through the electronic path—the greater the voltage, the greater the current, and the more rapid the rate of corrosion.

**Ohm's law and Faraday's laws.** The effects discussed in the previous paragraph can be expressed mathematically. Ohm's law states that the current flow through an electronic path will be equal to the voltage (the cell potential) divided by the resistance of the circuit. Thus,

$$I = \frac{E}{R} \quad (\text{Eq 2-1})$$

Where:

$I$  = current flow (A)

$E$  = potential or voltage difference (V)

$R$  = resistance (in ohms)

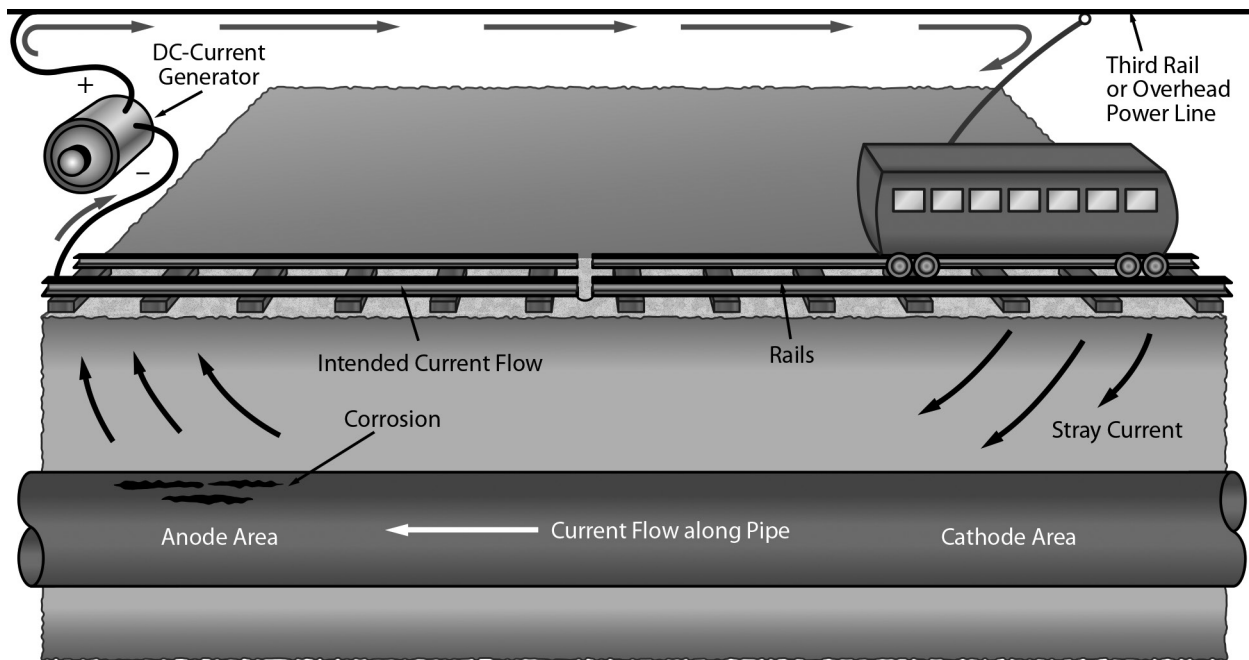


Figure courtesy of NACE International.

**Figure 2-7** Direct-current transportation system as a source of current causing electrolytic corrosion

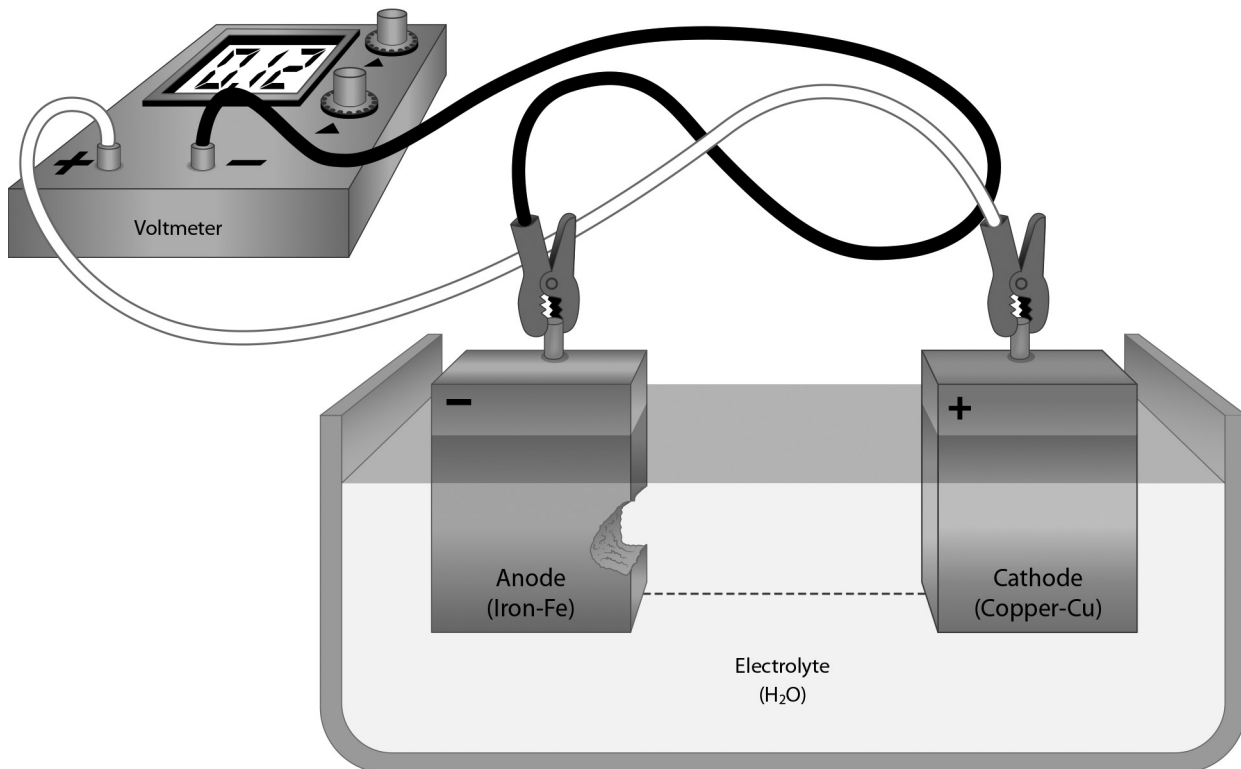


Figure courtesy of NACE International.

**Figure 2-8** Measuring cell voltage with a voltmeter

According to Faraday's law, the rate at which an anode of a given metal corrodes varies with the magnitude of electrical current flow and the electronic properties of the metal. For example, the corrosion rate for iron is 20 lb (9.1 kg) per ampere of current per year. Using Ohm's and Faraday's laws, the rate of current flow and the rate of corrosion can be calculated wherever the corrosion cell current is known.

## Galvanic Corrosion Materials

Galvanic corrosion cells can occur in many combinations of metals, alloys, and electrolytes found in all potable water production and distribution systems. In considering corrosion cells caused by differential metal combinations (known as *galvanic* or *bimetal couples*), it is essential to know which of the two metals involved will act as the anode and, therefore, corrode. It is also important to know how great the potential for corrosion will be for any two metals. The galvanic series for a given electrolyte supplies the answers to these questions.

**The galvanic series.** Table 2-1 shows a galvanic series typical for seawater. When any two metals in the series are combined with an electrolyte and an electronic path to form a galvanic cell, the metal nearer the top of the series will be the anode and corrode; the metal nearer the bottom will be the cathode and be protected. The metals on the cathodic end of the series are said to be more *noble* than those on the anodic end.

The farther apart two metals are in the series, the greater the cell voltage they will produce across the electronic path when immersed in the electrolyte. The cell voltage and the resistance of the circuit will determine how much current will flow and, therefore, how rapidly corrosion of the anode will occur. Thus, metals that are widely separated in the galvanic series will produce corrosion cells that demonstrate a high rate of corrosion, even when the electrical resistance of the circuit is high. Metals that are in close proximity in the series will produce cells where little or no corrosion occurs, because the voltage produced will seldom be sufficient to force a significant corrosive current to flow.

For the series shown in Table 2-1, the cell exhibiting the greatest corrosion would be formed with an anode of magnesium and a cathode of platinum, immersed in seawater and connected through an electronic path. The galvanic series shown in Table 2-1 is accurate where the electrolyte is seawater. Freshwater or moist soil exhibits slight variations in the arrangement of the metals in a galvanic series, and the magnitude of the cell voltage generated with electrodes of any two metals would also vary.

**Galvanic materials in water systems.** In most water systems, different equipment can contain components made of steel, gray iron and ductile iron, stainless steel, lead, brasses, copper, and bronzes. Many components are exposed only to treated water and may be subject to internal corrosion within the electrolyte of the treated water. The subject of internal pipe corrosion is beyond the scope of this manual. However, combinations of metals exposed externally do occur, notably where services, valves, or pumps are connected to mains.

For example, a brass curb stop connected to a wrought-iron service can be a source of considerable corrosion, as illustrated by the distance between brass and wrought iron in the galvanic series. A large valve may comprise several metals and alloys in its construction, with two alloys commonly used on the outside exposure: steel for nuts and bolts and cast iron for the valve body. It would appear that the two alloys are too close together in the galvanic series for corrosion to occur; however, the tendency for steel to act as an anode in a cell with cast iron is greatly magnified by the difference in surface areas between the small bolts and nuts and the much larger cast-iron valve body and bonnet. The same effect occurs in gray- or ductile-cast iron mechanical-joint bolts and nuts, as well as many other configurations within a water utility system where a small surface area of relatively anodic metal is in contact with a large surface area of relatively cathodic metal.

**Table 2-1 Galvanic series of selected metals and alloys (in seawater)\* at 25°C**

| <b>Anodic, Active End at Top of Series (Read Down)†</b> |                                                 |
|---------------------------------------------------------|-------------------------------------------------|
|                                                         | ↓                                               |
|                                                         | Manganese bronze                                |
|                                                         | Naval brass                                     |
| Magnesium                                               | Nickel (active)                                 |
| Magnesium alloys                                        | Inconel—76% Ni, 16% Cr, 7% Fe (active)          |
| Zinc                                                    | Yellow brass                                    |
| Aluminum 52SH                                           | Aluminum bronze                                 |
| Aluminum 4S                                             | Red brass                                       |
| Aluminum 3S                                             | Copper                                          |
| Aluminum 2S                                             | Silicon bronze                                  |
| Aluminum 53S-T                                          | Ambrac—5% Zn, 20% Ni, 75% Cu                    |
| Alclad                                                  | 70% Cu, 30% Ni                                  |
| Cadmium                                                 | Comp. G bronze—88% Cu, 2% Zn, 10% Sn            |
| Aluminum 17S-T                                          | Comp. M bronze—88% Cu, 4% Zn, 6.5% Sn, 1.5% Pb  |
| Aluminum 24S-T                                          | Nickel (passive)                                |
| Mild steel                                              | Inconel—75% Ni, 16% Cr, 9% Fe (passive)         |
| Wrought iron                                            | Monel—70% Ni, 30% Cu                            |
| Gray iron and ductile iron                              | 18-8 stainless steel, Type 304 (passive)        |
| Ni-resist                                               | 18-8, 3% Mo stainless steel, Type 316 (passive) |
| 13% Cr stainless steel, Type 410 (active)               | Titanium                                        |
| 50–50 lead–tin solder                                   | Silver                                          |
| 18-8 stainless steel, Type 304 (active)                 | Graphite                                        |
| 18-8, 3% Mo stainless steel, Type 316 (active)          | Gold                                            |
| Lead                                                    | Platinum                                        |
| Tin                                                     |                                                 |
| Muntz metal                                             |                                                 |
|                                                         | <b>Cathodic, Noble End at Bottom (Read Up)†</b> |

Source: [ASTM G82](#), Standard Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance. ASTM International, 2002. West Conshohocken, Pa.

\*Each environment has its own specific galvanic series. The relative positions of the various metals and alloys may vary slightly from environment to environment.

†In a galvanic cell of two dissimilar metals, the more active metal will act as the anode and be corroded, while the more noble metal will act as the cathode and be protected.

One good method of counteracting this differential effect of surface area is to provide greater nobility in the smaller metal unit. For example, ductile-iron pipe can be furnished with alloy steel coupling bolts containing copper, nickel, and chromium. This can minimize corrosion reactions, even in fairly conductive electrolytes.

The most severe galvanic corrosion occurs when two metals are installed that are widely separated in the galvanic series. However, due to intrinsic manufacturing non-homogeneity, even a single piece of metal equipment can have slight variations in the composition of its metal surface from one point to another. With a sufficiently strong electrolyte, these variations can produce microscopic galvanic corrosion cells, which can eventually expand and produce major deterioration of the metal.

## Polarization and Passivation

Two different phenomena that may reduce the rate of corrosion are polarization and passivation. Where appropriate, a design engineer may select materials that encourage these effects.

**Polarization.** As the products of a corrosion reaction build up at the anode and cathode, the voltage difference between the two tends to diminish. This is called *polarization*. The effect is likely to be greater at the cathode. For example, in acid solutions, hydrogen gas can literally blanket the cathode surface, tending to retard the flow of current. The hydrogen layer may be partially removed as hydrogen gas combines with oxygen gas, forming water. This is more pronounced on a comparatively large cathode because the hydrogen is spread thinly over a large surface area. Hence, it is preferable to have a large anode and small cathode than the reverse.

Even so, the anode can become polarized by a layer of oxide film or other compound that has the effect of forming a barrier between the metal and its environment. Some metals polarize more easily than others; therefore, metal selection can be an important part of engineering.

**Passivation.** Passivation is a condition in which a given metal behaves in the manner of a more noble metal than is indicated by its position in the galvanic series. It is a condition of electrochemical activity where the initial corrosion products of certain metals provide protection of the base metal.

**Passivation of steel in concrete.** Steel embedded in concrete becomes corrosion resistant. The curing of concrete is a process called hydration, where the cement in freshly placed concrete develops a high alkalinity. The alkalinity of the concrete forms a passive oxide film on the surface of the steel due to the initial corrosion reaction. The passive film that forms isolates the steel from the environment and stops further corrosion as long as the film is intact. That alkalinity, in the presence of oxygen, stabilizes the initial corrosion film on the surface of the embedded steel and ensures protection while the alkalinity is maintained. Typically, concrete would have a pH of 12 or above because of the presence of calcium hydroxides. When passivated, the steel behaves in the manner of a more noble metal than is indicated by its position in the galvanic series. That is also seen by measuring its potential to a half cell. Typically, bare steel will have a potential of  $-500$  mV to  $-700$  mV to a copper–copper sulfate half-cell; passivated in concrete, its potential rises to  $-200$  mV.

## Specific Types of Corrosion in Water Systems

In water utility systems, situations commonly occur in which a combination of environmental factors, physical configurations, and materials can accelerate corrosion. The following paragraphs describe some of those conditions and their effects.

**Concentration cells.** Concentration cells (Figure 2-9) are localized occurrences of corrosion that often develop at crevices in metal units due to the uneven diffusion of oxygen.

Oxygen content inside the crevice may be low compared with that in the environment just outside the crevice. In this case, metal near the lower oxygen concentration will become anodic, and corrosion will occur within the crevice.

**Pitting corrosion.** When protective films covering a metal, metallic layers, or the uniform surface of a metal break down, corrosion occurs as pitting (Figure 2-10). The metal within the pit area is anodic and the surrounding area is cathodic.

**Impingement corrosion attack.** As a result of the manufacturing process, many metals can form protective surfaces under normal operating conditions. Physical impact, such as a strong stream of water, can break through this protective surface and produce corrosion (Figure 2-11). Pumps are especially vulnerable to this type of attack because of *cavitation*, the abrasive effect caused by the collapse of bubbles formed by extreme pressure differentials within the pump mechanism.

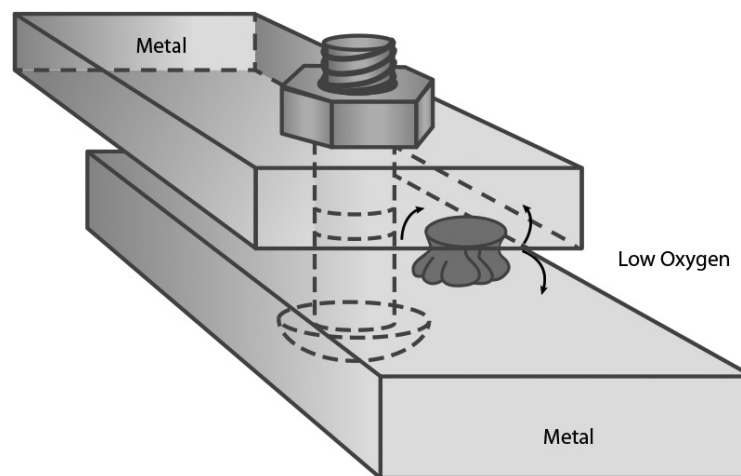


Figure courtesy of NACE International.

**Figure 2-9** Concentration cell (crevice) corrosion

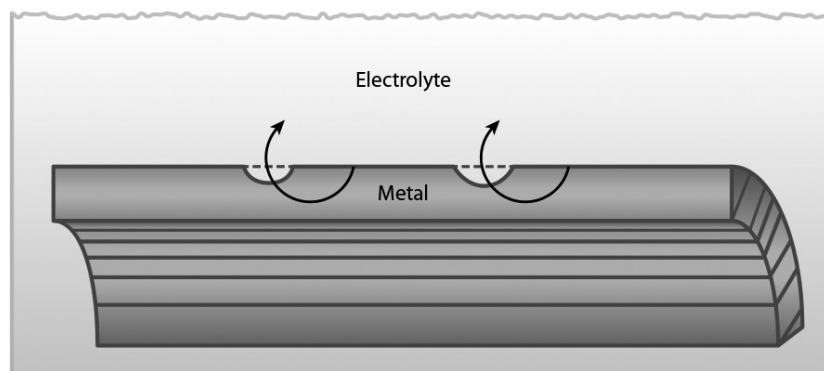


Figure courtesy of NACE International.

**Figure 2-10** Pitting corrosion (arrows indicate positive current flow)

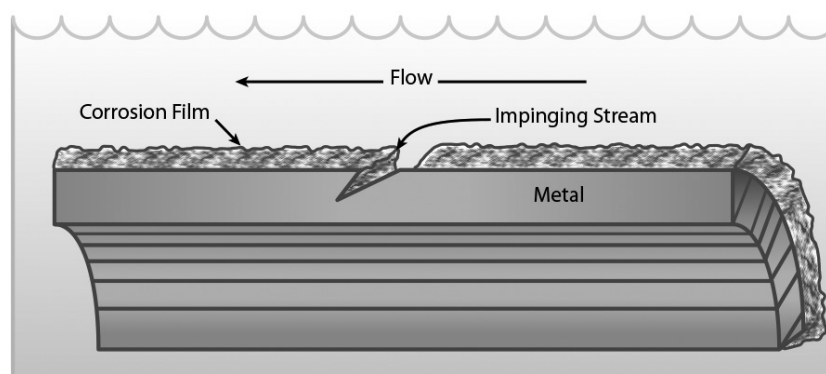


Figure courtesy of NACE International.

**Figure 2-11 Impingement corrosion**

**Microbiologically influenced corrosion (MIC).** MIC refers to corrosion brought about by the presence and/or activities of microorganisms in biofilms on the surface of the corroding material. Most materials, including metals, some polymers, glass, and ceramics, can be degraded in this manner.

A number of microbiological organisms, notably bacteria, fungi, and algae, have been associated with corrosion damage in water systems. These microorganisms can influence corrosion by effects such as differential aeration cells, the production of corrosive species such as mineral and organic acids, ammonia, and reduction of sulfate to sulfide. The various types of microbes tend to act synergistically in the corrosion of materials with their interactions typically being of a complex nature.

By-products of sulfate-reducing bacteria cause bacteriological corrosion (Figure 2-12). These bacteria live in environments where little or no oxygen is present and the pH is near neutral. Their life processes reduce sulfates to sulfides that are excellent electrolytes and depolarizers and are otherwise aggressive to metal surfaces.

In the metabolic process of any living thing, there is an electrodynamic balance, as energy is either required or released during the functioning of the organism. In some species of bacteria, these energy changes induce a measurable electric current. When corrosion-causing microorganisms reproduce on the surface of iron pipe, electrobiochemical removal of iron occurs, causing corrosion. Sulfate-reducing bacteria have been found to cause the electrode potential of stainless steel to shift 150 mV to the negative side.

Microorganisms can participate in iron and steel corrosion by creating conditions favorable to electrochemical reactions. For example, their metabolism can change the surface film resistance with such products as sulfuric and organic acids. In other instances, slime deposits may shield some areas so that they become anaerobic even with considerable oxygen present in the water. The anaerobic sites on the metal surfaces become anodic to the aerobic areas.

The most important bacteria associated with corrosion are the sulfate reducers or sulfide formers. They are classified as either nonsporulating (*Desulfovibrio*) or spore-forming (*Desulfotomaculum*, which include the *Clostridium nigrificans*).

Sulfate-reducing bacteria use the sulfate ion as the terminal electron acceptor for their respiration. These organisms are also autotrophic in using an inorganic source of carbon. Energy is obtained by the reduction of the sulfate ion by hydrogen, which can come from molecular hydrogen or organic compounds. In metabolism, the organisms can use molecular hydrogen for producing  $H_2S$ . Corrosion usually results by cathodic depolarization, and it is greatly accelerated by the organism's consumption of hydrogen.