# External Corrosion—Introduction to Chemistry and Control

MANUAL OF WATER SUPPLY PRACTICES—M27, Second Edition

**AWWA MANUAL M27**

*Second Edition*

**American Water Works Association**

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# External Corrosion—Introduction to Chemistry and Control

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# Introduction

Corrosion prevention and control is a practical science that allows relatively reliable predictions of corrosive conditions and, more important, effective prevention or mitigation of corrosion where economically appropriate. Faced with how best to install and protect a distribution system to minimize corrosion, today's water utility manager must evaluate the cost of corrosion protection compared with the extended life of the 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 both 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 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, the relevant sections of *Basic Science Concepts and Applications*[*] are recommended.

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/mitigation materials, it is the responsibility of the operator to ensure that materials in contact with the water supply have been properly tested and certified in accordance with the standards and regulations relevant to the water utility involved.

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[*] *Basic Science Concepts and Applications,* American Water Works Association, Denver, Colorado (2003).

# Contents

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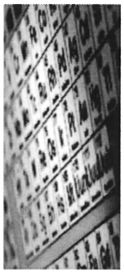


## Chapter 1

# 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 an electrochemical reaction that deteriorates a metal or an alloy.

This chapter presents a brief introduction to the science and terminology of corrosion, 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 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; and
- recognize the responsibilities for a corrosion-control effort that must be assumed by various utility personnel.

## CORROSION—OCCURRENCE AND IMPLICATIONS

For the purposes of this manual, corrosion also includes the dissolving of other water system materials through contact with water or soil.

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 (2001) recently released a 2-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 impact 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

There are several conditions that 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;
- microbiologically induced 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, and many others, is 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 soils, and alkali soils are corrosive. Low, poorly drained soils are more likely to be corrosive than those in well-drained areas. The corrosivity (also called aggressiveness) of a given soil can be determined by sampling, testing, and analysis.

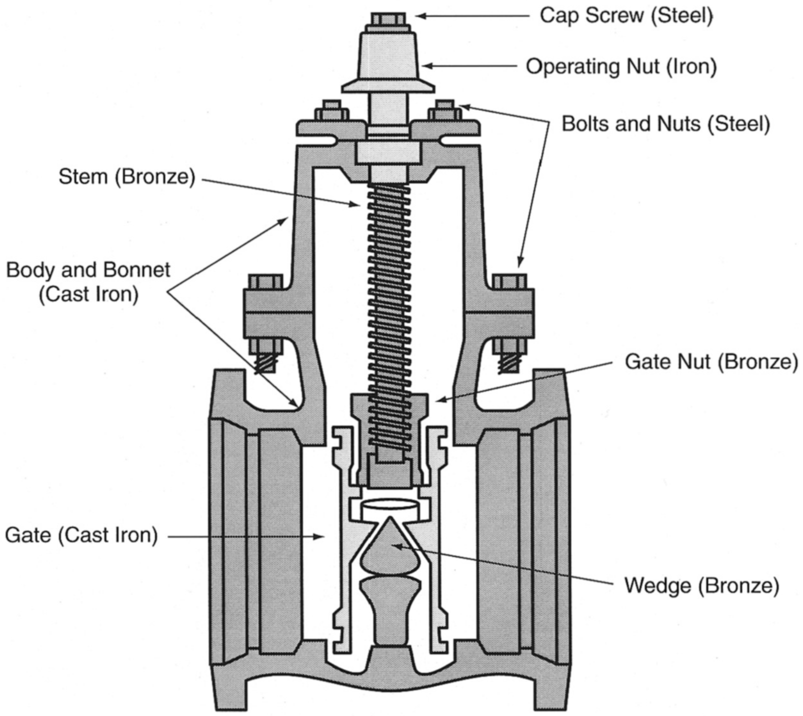


Figure 1-1 Metals used in a typical gate valve

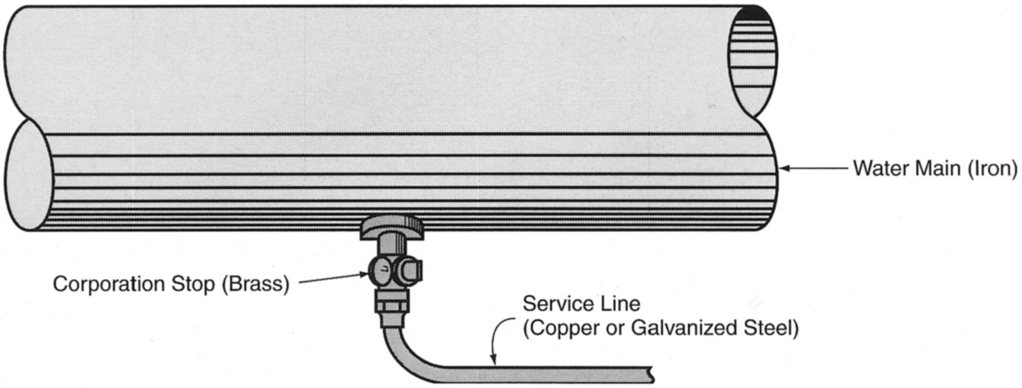


Figure 1-2 Metals used at a typical water-service-to-main connection

**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.

**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, then later paved. Cinders are aggressive to most pipe and valve materials, and their presence is a warning that serious corrosion may occur.

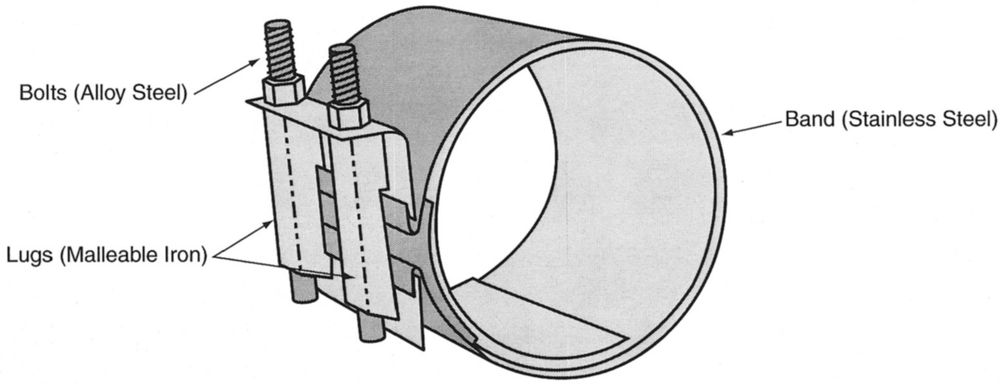


Figure 1-3 Metals used in a pipe-repair clamp

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 alternate locations are not feasible, the potential for corrosion must be considered.

**Microbiologically induced corrosion.** Some types of anaerobic bacteria can produce hydrogen sulfide, which in turn can promote corrosion of subsurface base metals. Other bacteria can produce such compounds as sulfuric acid, sulfates, and ferric hydroxide—all of which may increase the corrosivity of the environment.

## Implications of Corrosion

There are limited sources of information detailing the 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 probably substantial.

In addition to the financial impact of repair, replacement, labor, and equipment, there are other, more important costs to 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 spread 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

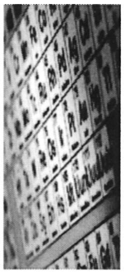
There are two primary considerations involved in any decision regarding corrosion control. The first, and most important, is the protection of public health and safety. The second is economics. Both publicly owned and investor-owned utilities must operate effectively and efficiently.

In either case, faced with decisions regarding what corrosion-control programs to implement, water utility staff must determine which actions will produce the lowest overall cost and the highest return of capital. The staff must decide which alternative is preferable: (1) minimize initial costs and accept higher maintenance costs and shorter equipment life or (2) increase initial investment by specifying extensive 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, Office of Infrastructure Research and Development. 2001. *Corrosion Costs and Preventive Strategies in the United States.* Report FHWA-RD-01-156 from CCC Technologies Laboratories, Inc.



## *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, the basic chemical and electrical reactions of corrosion are explained, and several water utility system configurations are described where corrosion commonly occurs.

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; and
- 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. There are two basic types of corrosion in a water system: galvanic corrosion and electrolytic corrosion. This section discusses the basic physical configurations and chemistry of both types.

### 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 return current path. Figure 2-1 shows the elements of a galvanic corrosion cell. Note the solid arrows indicating the direction of electron movement and the screened arrows indicating current flow.

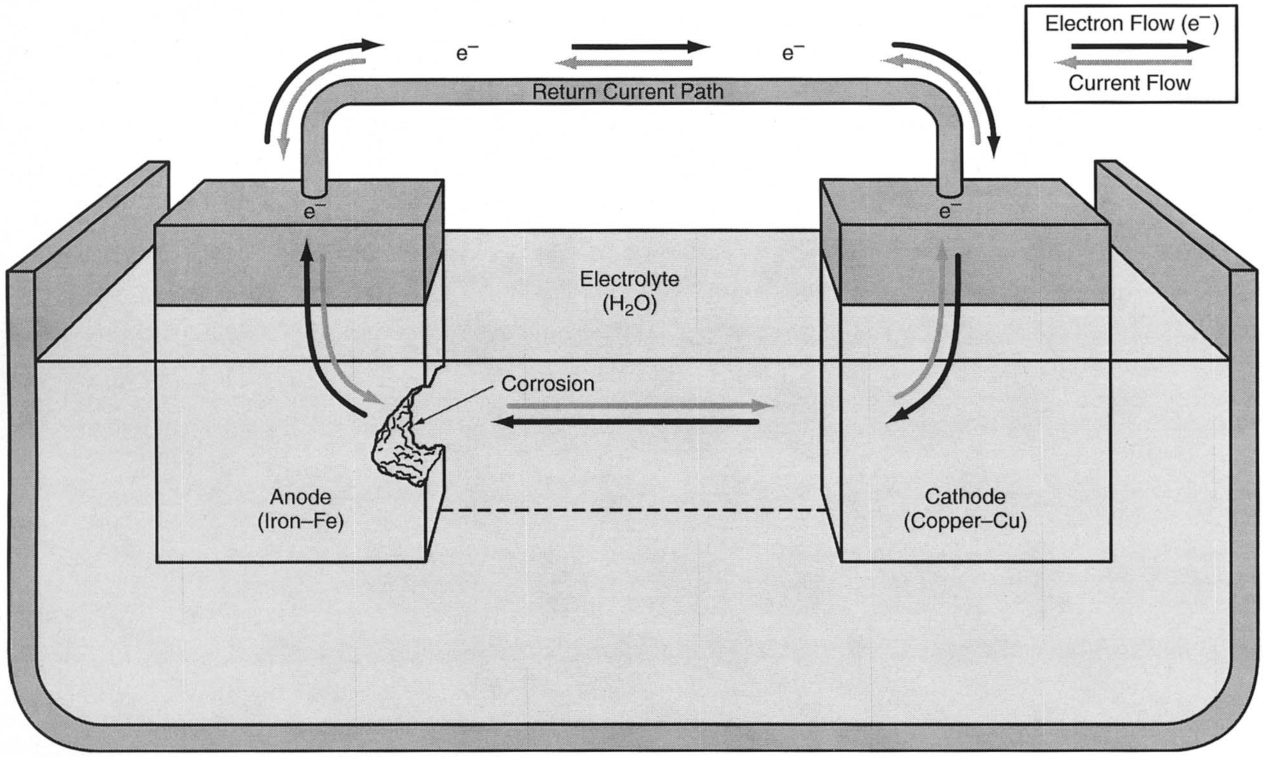


Figure 2-1 The four basic elements of a galvanic corrosion cell: anode, cathode, electrolyte, and return current path

In the galvanic cell, corrosion takes place at the surface of the electrode where electrons are generated to travel through the electronic 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 return current path—must exist before corrosion can occur.

**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 ($Fe^o$) to ferrous iron ($Fe^{2+}$) and then to ferric iron ($Fe^{3+}$), leaving them with a strong positive charge. Some of the molecules of the electrolyte, in this case pure water ($H_2O$), are naturally separated into hydrogen ions ($H^+$) with positive charges and hydroxyl ions ($OH^-$) with negative charges. The positively charged iron atoms are attracted to the negative $OH^-$ ions. The attraction causes the iron atoms to leave the anode and enter the electrolyte, where they combine with $OH^-$ ions. As atoms are lost, the metal surface of the anode deteriorates. This deterioration is corrosion. Note that the products of corrosion, $Fe(OH)_2$ and $Fe(OH)_3$, may accumulate on or near the corroded surface.

At the cathode, the negatively charged electrons arrive from the electronic path. The electrons are attracted to the positively charged $H^+$ ions in the electrolyte. The attraction causes the electrons to leave the cathode and combine with the $H^+$ ions, forming hydrogen gas ($H_2$). 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

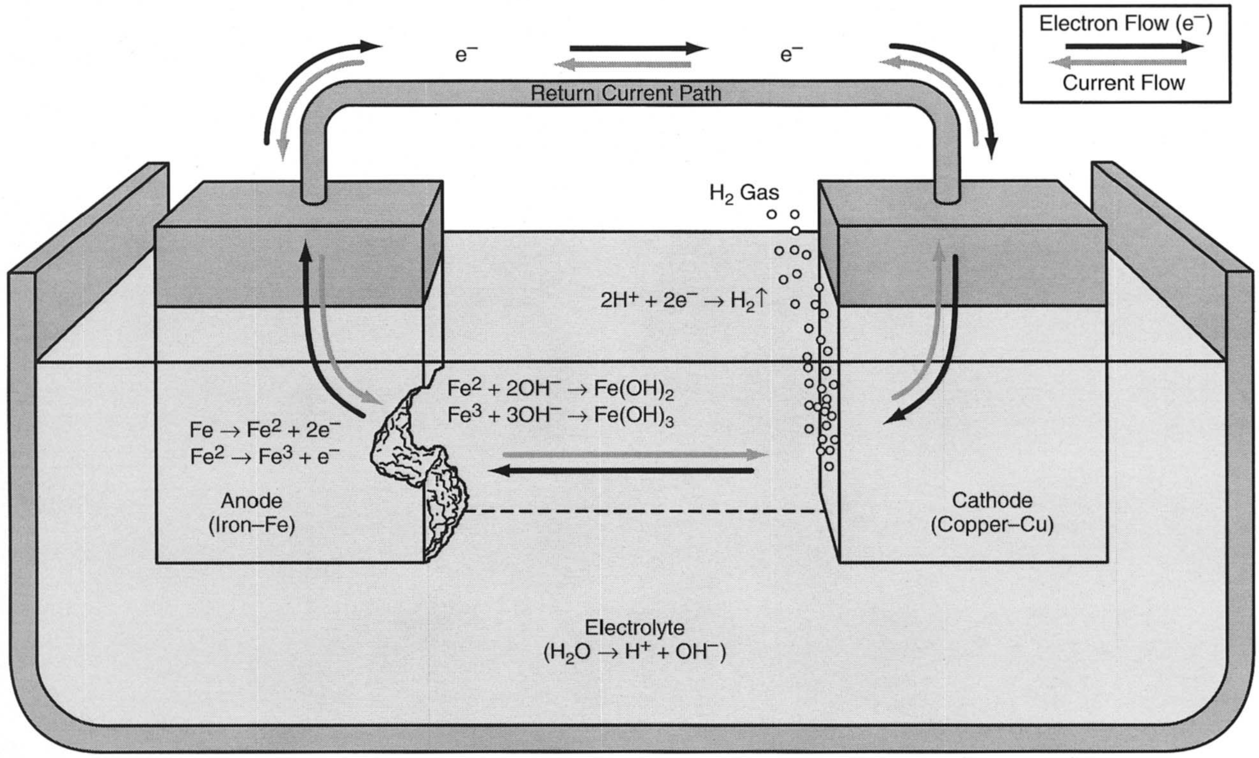


Figure 2-2 Chemical reactions in a typical galvanic corrosion cell

corrosion cell actually protect the cathode from corrosion. This fact forms the basis for cathodic protection (chapter 4).

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 ($OH^-$) 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 a solid 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 electrons 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 return current path. Figure 2-4A shows the same configuration as Figure 2-3—two electrodes of the same metal in a

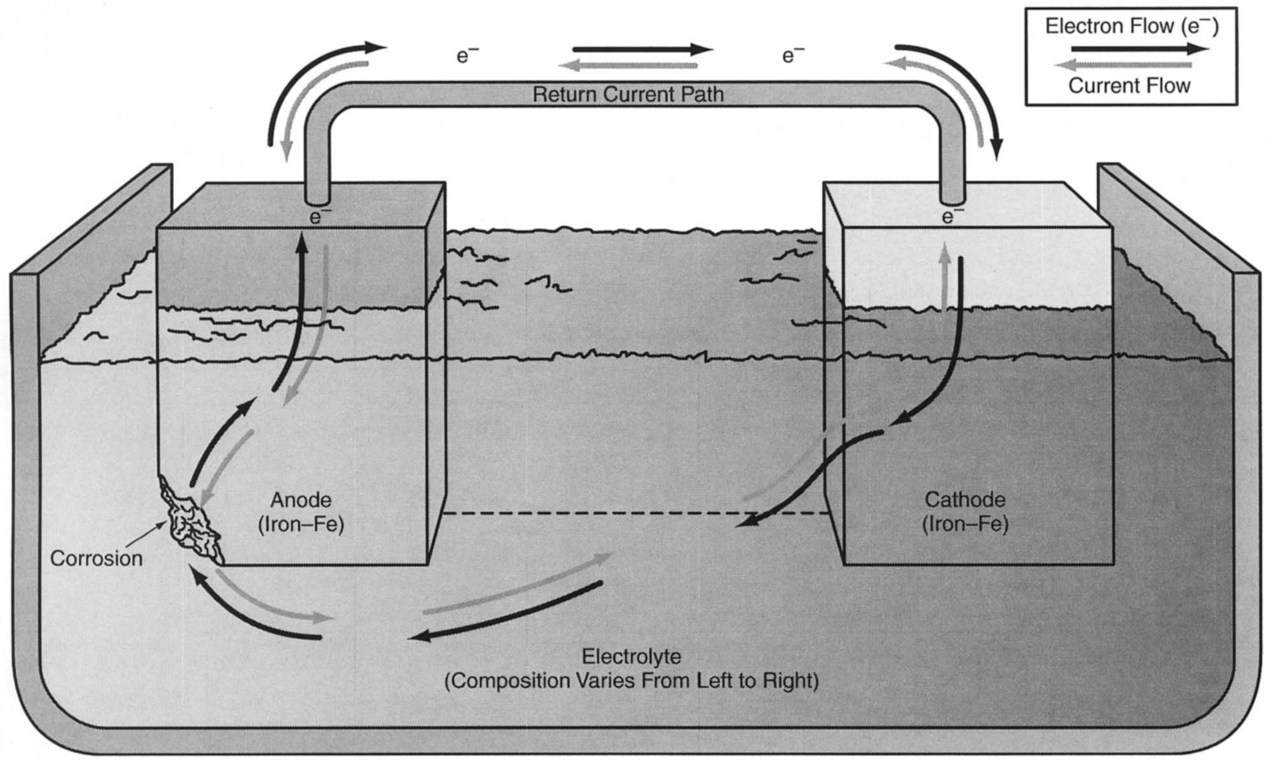


Figure 2-3 Galvanic cell formed with nonuniform electrolyte and electrodes of a single metal

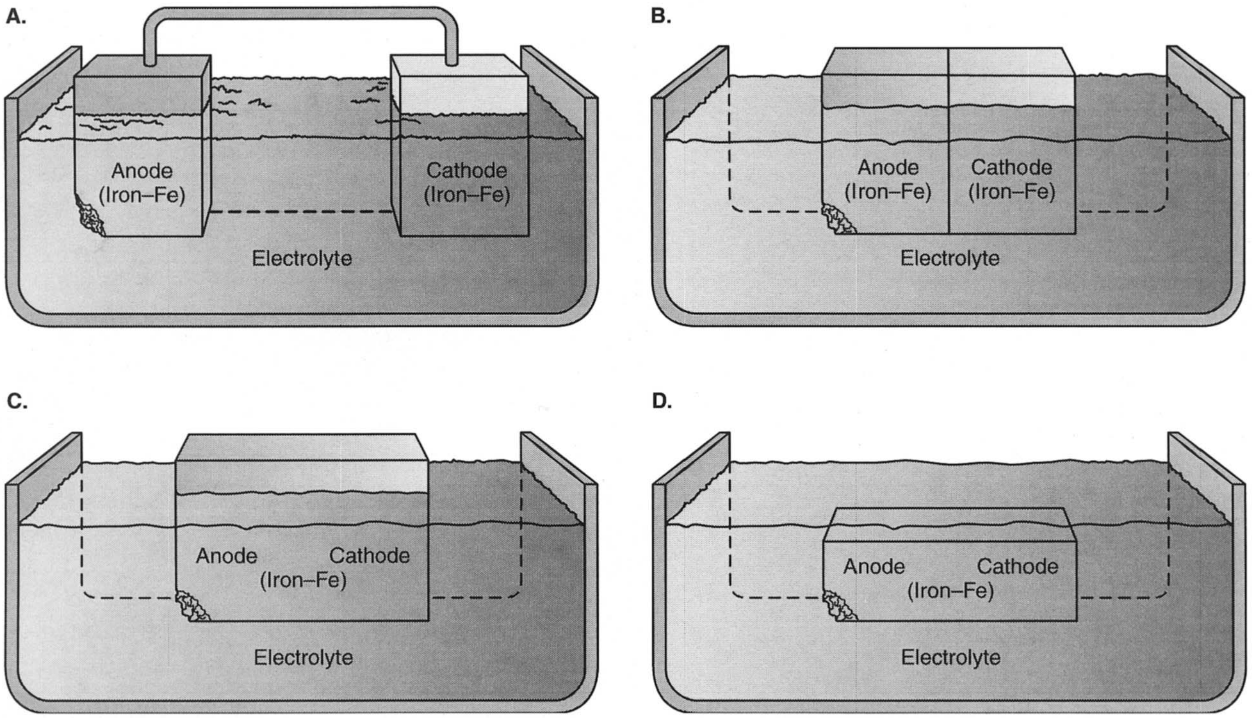


Figure 2-4 Creating a galvanic cell with a single piece of metal in a nonuniform electrolyte

nonuniform 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 uneven electrolyte, which could be soil. However, the effect remains the same as in the original configuration—the metal corrodes in the area acting as the anode.

Because soil is often nonuniform, there is always a possibility that such corrosion cells can develop around underground metal structures. Whether the cell causes significant damage depends on the strength 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 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, where electrons enter the electrolyte, 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

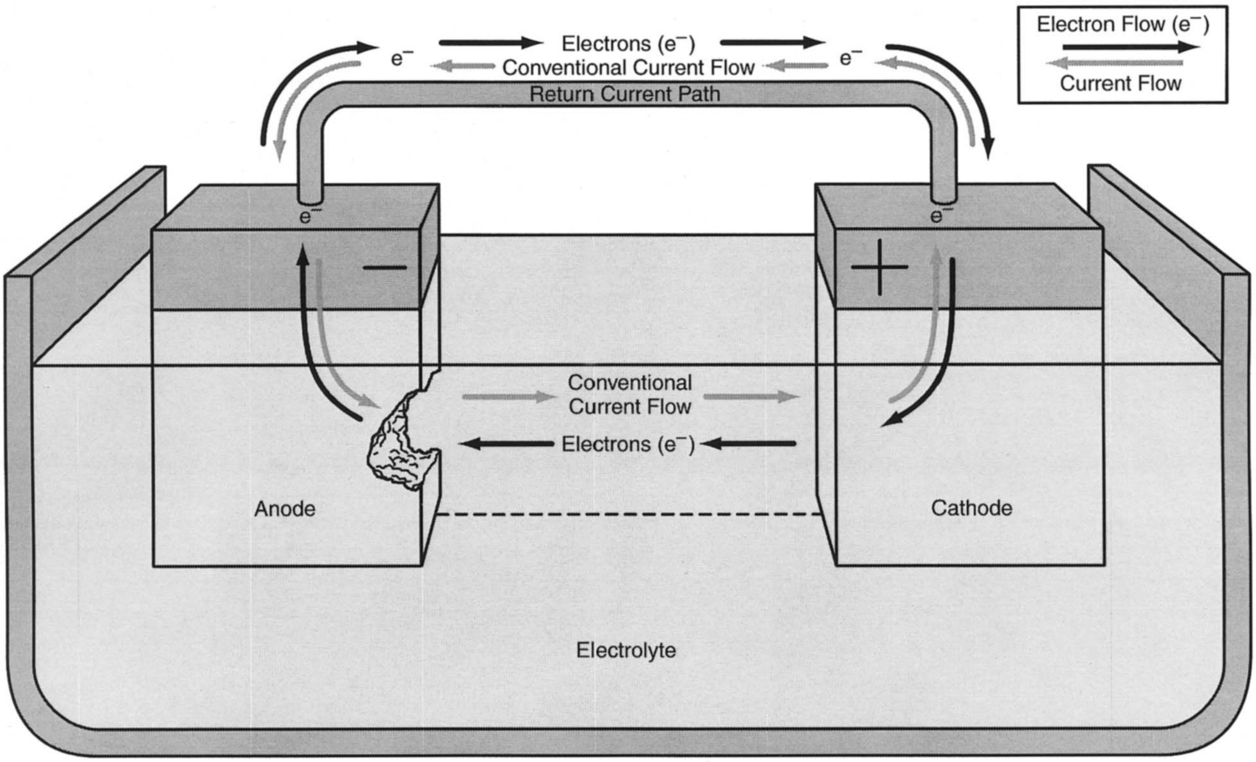


Figure 2-5 Contrasting conventional current flow with electron movement in a galvanic corrosion cell

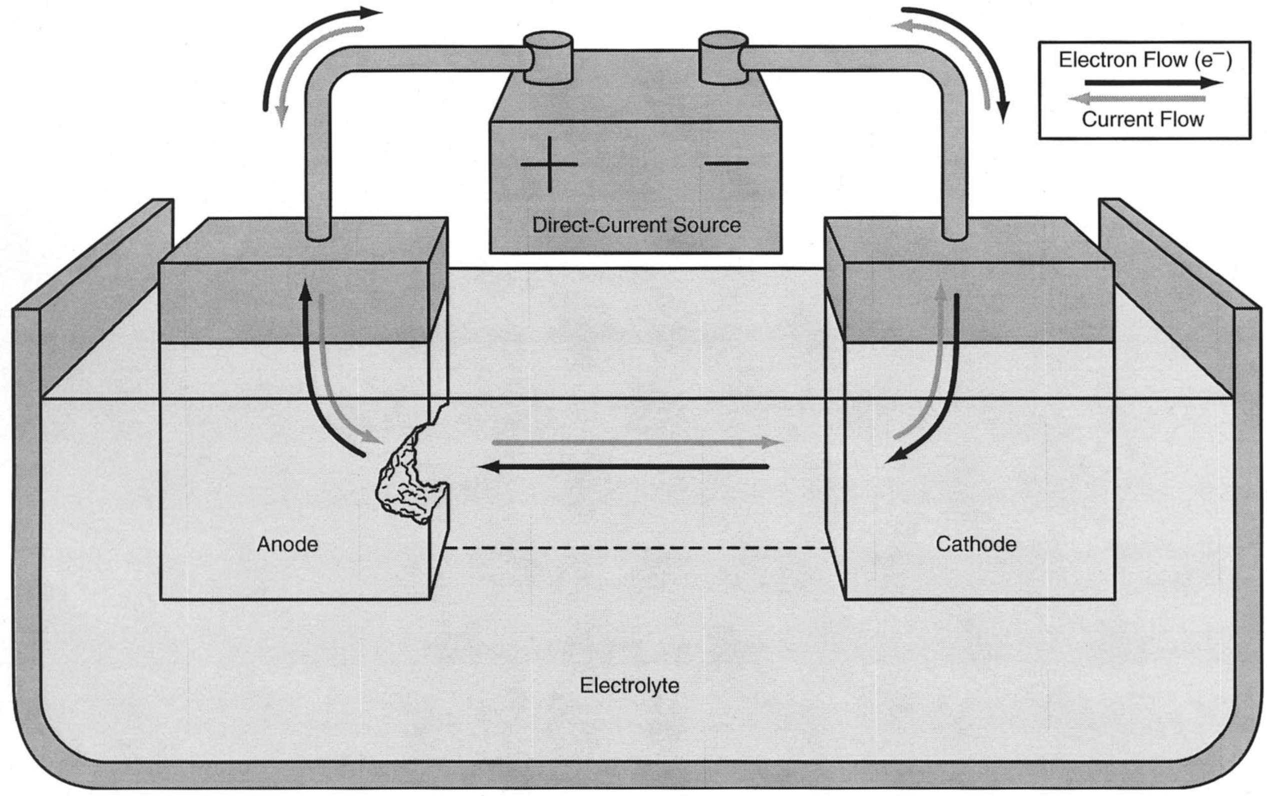


Figure 2-6 A typical electrolytic corrosion cell

metals 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 connecting current path. At the location of current discharge from the anode into the electrolyte, there is loss of anode metal. 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 a return current 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 driven by a direct-current source originating outside the cell. However, the end result is the same—corrosion of 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 return current path. In addition, an outside direct-current source, located within the return current 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. There are several situations where the external direct current needed to drive electrolytic corrosion may occur in the area of a water distribution system. Direct-current–driven train or subway systems can be a source of stray current if

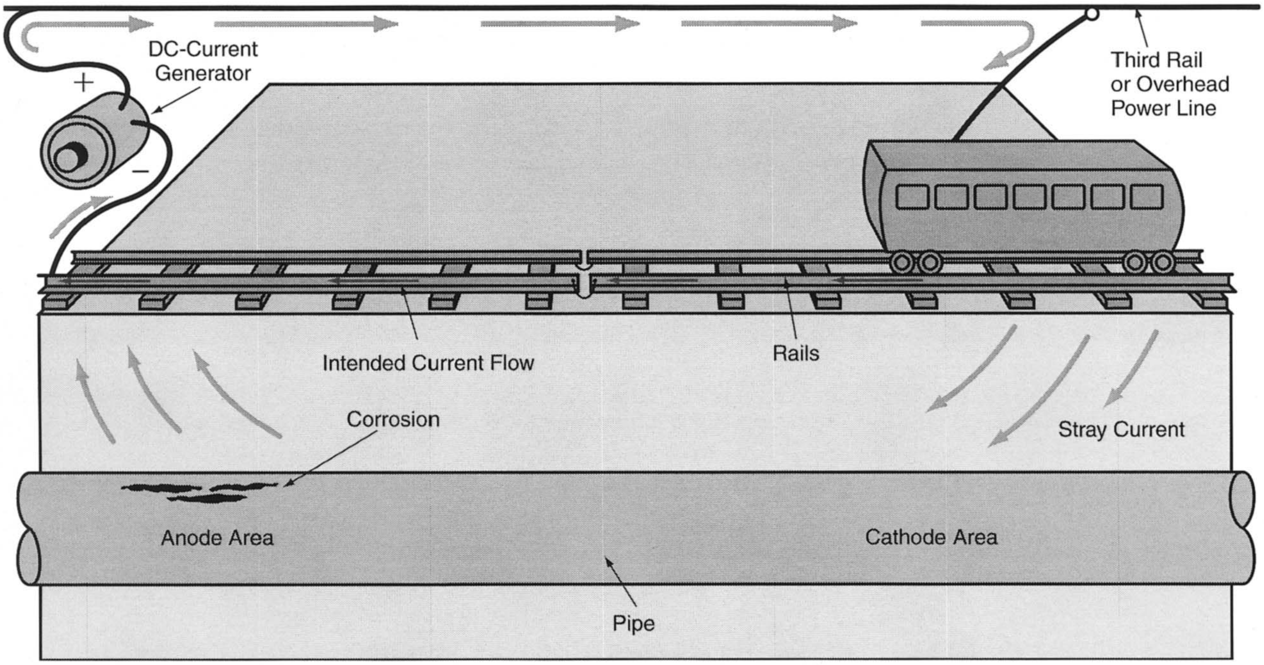


Figure 2-7 Direct-current transportation system as a source of current causing electrolytic corrosion

the rails (the system's intended return current path) are not completely insulated 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 effect on metal at the point of discharge as direct current and generally does not cause corrosion. In some cases, alternating current traveling from an underground source can become rectified to direct current, which can cause corrosion.

## 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, then 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 return current 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.

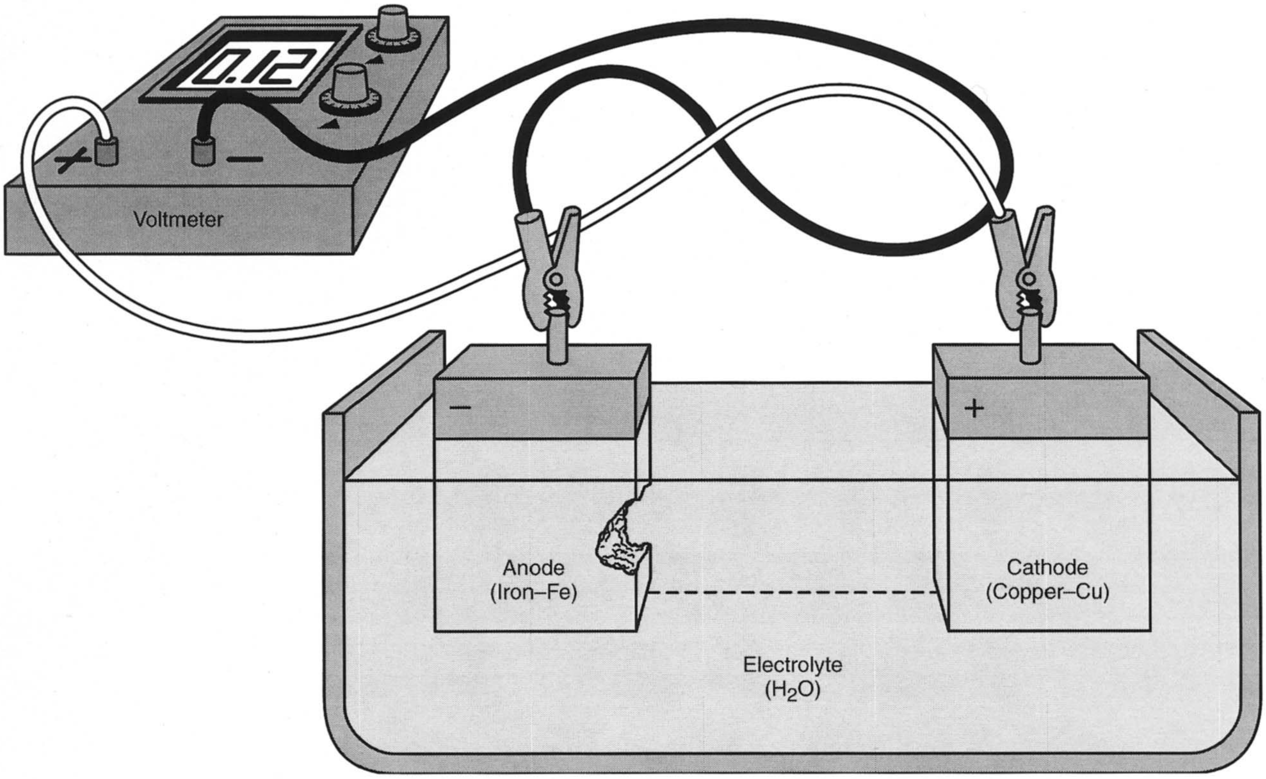
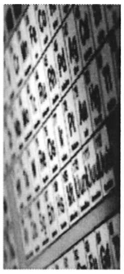


Figure 2-8 Measuring cell voltage with a voltmeter



# Chapter 3

# Evaluating the Potential for Corrosion

External corrosion of water utility piping and equipment is not inevitable. Certain combinations of materials in certain environments may suffer serious corrosion at a rapid rate, while other configurations may be relatively immune. For the purposes of both design and operations, it is important to be able to predict the occurrence and severity of corrosion.

For metallic corrosion to occur, four elements are required: an anode, a cathode, an electrolyte, and a conductive path for return current. Dissimilar metals and alloys are commonly found in contact in water utility installations, and even a single piece of metal can simultaneously act as anode, cathode, and return current path. In either case, the electrolyte is a key variable in determining where and to what extent corrosion will occur. For external corrosion, the electrolyte is the environment—the soil or water surrounding the equipment.

Many environmental conditions will not support corrosion. Other environments serve as a damaging electrolyte for some metals, alloys, or metallic pairs but not for others. To evaluate an environment for a given material, experience provides the best guide. In the absence of experience, as in the case of new locations, analytical procedures should be used. If either experience or analysis shows the environment to be aggressive, corrosion prevention or control should be initiated.

This chapter details the relationships among specific materials and environmental conditions commonly found in water utility installations, then concludes with a discussion of monitoring for stray electrical currents that may cause electrolytic corrosion.

After completing this chapter, the reader should be able to

- understand the influence of environment on the corrosion process;
- realize that a given environment may cause corrosion in one material but not in another;
- be alert to many of the environmental conditions that cause corrosion;

- have a general understanding of the systems used to determine whether soils are corrosive to various materials; and
- understand how stray direct current can affect underground metallic structures and recognize some of the common sources of stray current.

# EFFECTS OF THE CHEMICAL ENVIRONMENT ON COMMON WATER PIPE MATERIALS

The effects of soil, water, and air on a pipe vary greatly depending on the pipe material. This section discusses environmental effects and evaluation procedures for materials commonly used in water utility pipe and appurtenances.

## Gray-Iron and Ductile-Iron Pipe

Several soil evaluation procedures for gray-iron and ductile-iron pipe installations have been developed. Because of the complexity of subsurface corrosion, no system is universally applicable and no system can replace the need for expertise in the field of corrosion control. The evaluation system originally developed and recommended by the Ductile Iron Pipe Research Association, commonly referred to as the 10-point system, is discussed in detail in the following text. This soil evaluation procedure is specific to gray-iron and ductile-iron pipe and should not be applied to other materials.

Appendix A of ANSI/AWWA C105/A21.5-99, *Standard for Polyethylene Encasement for Ductile-Iron Pipe Systems*, covers the soil-survey tests, observations, and interpretations that comprise the 10-point system. The soil evaluation system was introduced in 1968 and adopted as an appendix to the standard in 1972. It was based on field experience with operating gray-iron pipelines, where soil-test results were recorded along with the age of the pipe and its condition, including extent and type of corrosion. Most of the experience was with gray-iron pipe. As ductile-iron pipe became more widely available, it was necessary to determine whether the same tests and evaluation could also be accurately applied. Field research has demonstrated that the overall corrosion rates of ductile and gray iron are such that the soil evaluation system can be applied to both with equal accuracy.

The evaluation procedure is based on the result of five soil tests and observations: (1) soil resistivity, (2) pH, (3) redox potential, (4) sulfides, and (5) moisture. For a given soil sample, each result is evaluated and assigned points according to its contribution to corrosivity. The points for all five criteria are totaled. If the sum exceeds 10, the soil is considered corrosive to gray-iron or ductile-iron pipe, and corrosion will likely occur unless protective measures are taken (as discussed in chapter 4). Table 3-1 lists the scoring criteria for the various tests. The following sections provide additional detail on each area of evaluation.

**Soil resistivity.** A soil-resistivity test yields the reciprocal of conductivity; low soil resistivity indicates that it will serve well as an electrolyte. Resistivity, reported in ohm-centimeters (Ω-cm), represents the average of the electrical resistances across each cubic centimeter of soil in a given volume. The test may be accomplished by several means. To determine average resistivity from near ground surface to pipe depth or below, the 4-pin system may be used (Figure 3-1).

The 4-pin system has limitations because it may average dry topsoil with wetter subsoil, contaminated soil with clean soil, etc. Use of a single soil probe (Figure 3-2) is preferred by some corrosion technicians for field tests. The probe is suitable for specific readings at various soil depths, enabling the surveyor to search out the lowest resistivity soil that may come in contact with pipe after it has been buried.

Because soil moisture affects resistivity and moisture in the field may vary unpredictably, it is advisable to remove a soil specimen from pipe depth for laboratory testing.

Table 3-1 Soil-test evaluation for ductile-iron pipe (10-point system)

| Soil Characteristics Based on Samples Taken Down to Pipe Depth | Points* |
|---|---|
| **Resistivity**—*Ω-cm*† | |
| <1,500 | 10 |
| ≥1,500–1,800 | 8 |
| >1,800–2,100 | 5 |
| >2,100–2,500 | 2 |
| >2,500–3,000 | 1 |
| >3,000 | 0 |
| pH | |
| 0–2 | 5 |
| 2–4 | 3 |
| 4–6.5 | 0 |
| 6.5–7.5 | 0‡ |
| 7.5–8.5 | 0 |
| >8.5 | 3 |
| Redox potential | |
| > +100 mV | 0 |
| +50 to +100 mV | 3.5 |
| 0 to +50 mV | 4 |
| Negative | 5 |
| Sulfides | |
| Positive | 3.5 |
| Trace | 2 |
| Negative | 0 |
| Moisture | |
| Poor drainage, continuously wet | 2 |
| Fair drainage, generally moist | 1 |
| Good drainage, generally dry | 0 |

*Source:* Based on appendix A in AWWA/ANSI C105.

* Ten points—corrosive to ductile iron pipe, protection is indicated.

† Based on water-saturated soil box.

‡ If sulfides are present and low or negative redox-potential results are obtained, three points shall be given for this range.

The quad-box (Figure 3-3) or a similar unit makes it possible to water-saturate the soil, apply salts in solution, and simulate the most aggressive conditions likely to occur after pipe installation.

**pH.** Soils with a pH below 4.0 are acidic in nature and generally serve well as an electrolyte, and thus are considered aggressive. Neutral pH (6.5–7.5) indicates that the soil may support sulfate-reducing bacteria if other characteristics are suitable. Soils with a high pH (8.5–14.0) possess high concentrations of dissolved salts and usually exhibit low resistivity. Figure 3-4 illustrates equipment for measuring pH. Shown are a pH meter, a pH-sensing electrode, and a reference electrode. The pH sensing electrode and reference electrode can also commonly be found combined into a single electrode referred to as a combination pH electrode.

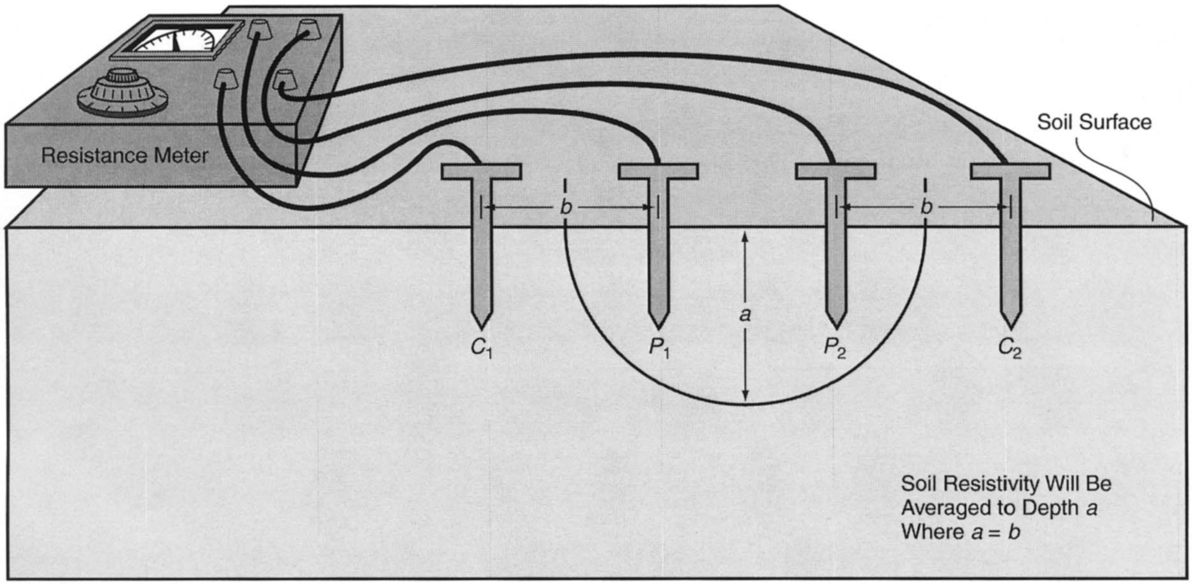


Figure 3-1 The 4-pin system of soil-resistivity testing

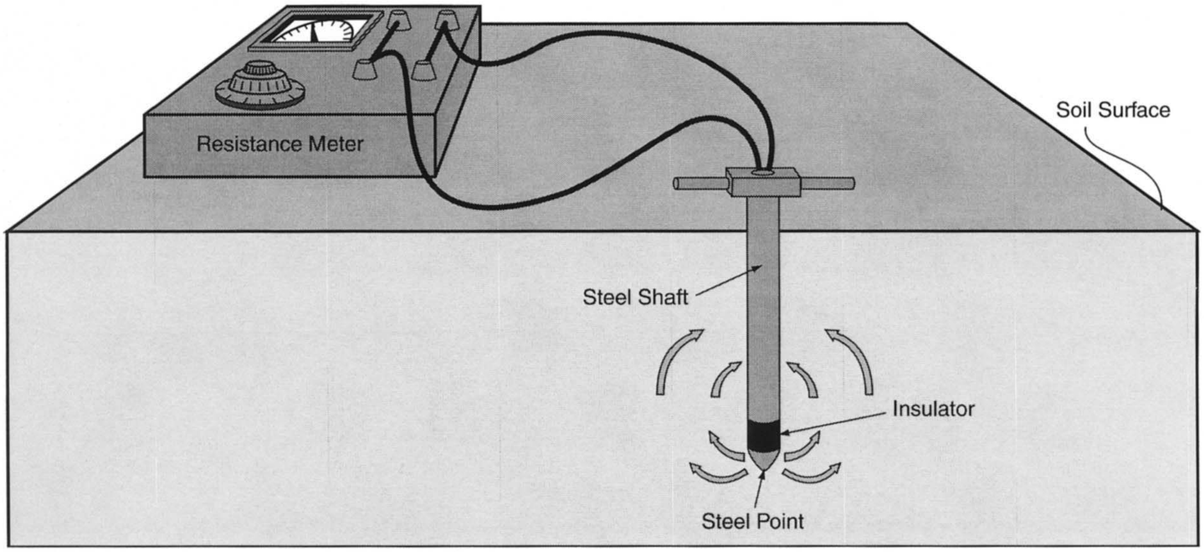


Figure 3-2 Use of a single probe for testing soil resistivity

**Oxidation-reduction (redox) potential.** A test of the oxidation-reduction potential indicates the degree of soil aeration. Low or negative results indicate that the soil is anaerobic and can support sulfate-reducing bacteria. The redox test can be performed with the same meter used to measure pH, using a platinum electrode in conjunction with the reference electrode used for pH. As with the pH electrodes, these electrodes can be combined into a single combination redox electrode. The sample should be protected from exposure to the atmosphere until tested.

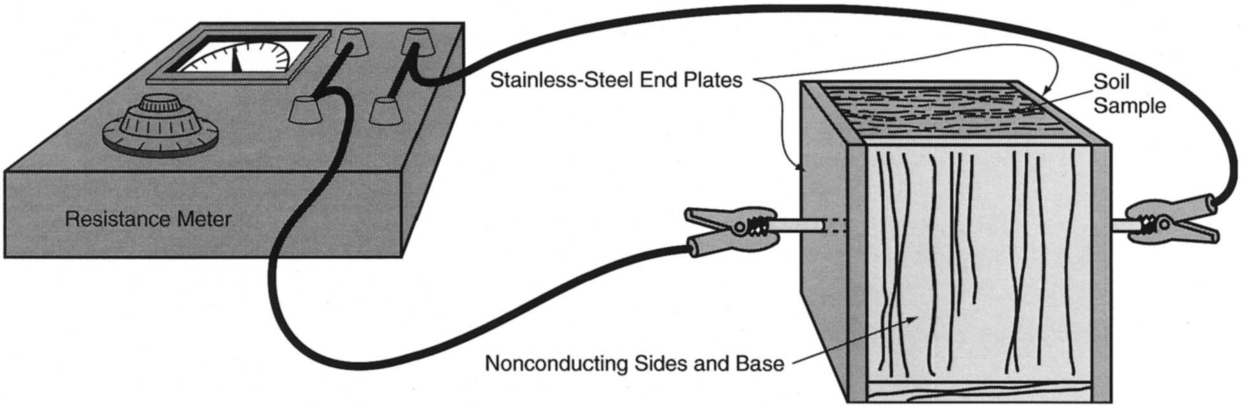


Figure 3-3 Quad-box for testing resistivity of a water-saturated soil sample

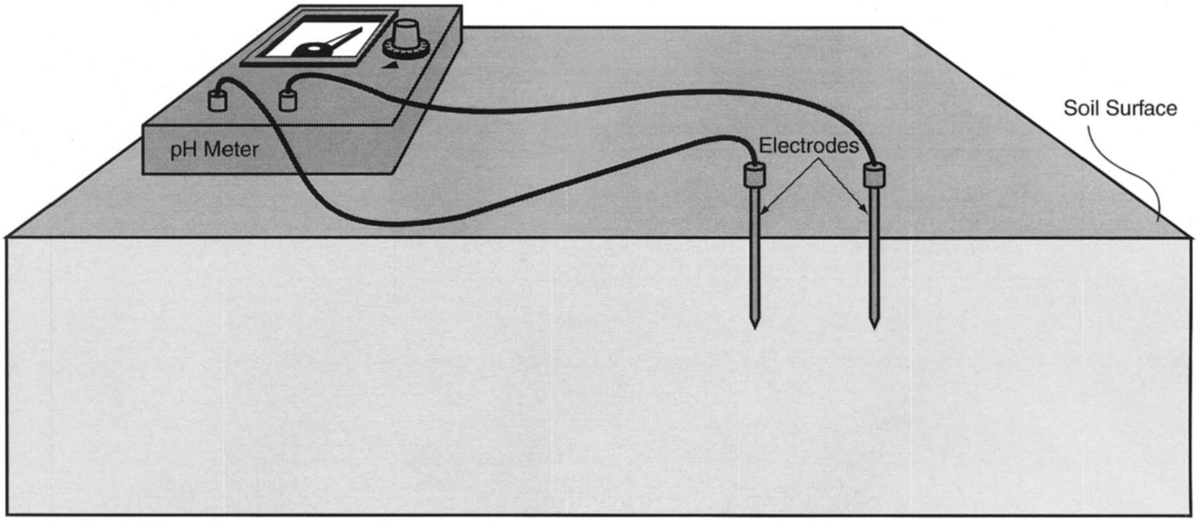


Figure 3-4 Testing soil pH

**Sulfides.** Soils containing elevated sulfide concentrations usually indicate the presence of sulfate-reducing bacteria. The sulfides test is qualitative and accomplished by introducing a solution of 3 percent sodium azide in 0.1*N* iodine into a test tube containing a small quantity of soil obtained from pipe depth. If sulfides are present, they catalyze a reaction between sodium azide and iodine with the release of nitrogen. The chemical reaction is

$$\underset{\substack{\text{Sodium}\\\text{Azide}}}{2NaN_3} + \underset{\text{Iodine}}{I_2} \rightarrow \underset{\substack{\text{Sodium}\\\text{Iodide}}}{2NaI} + \underset{\text{Nitrogen}}{3N_2}$$

**Moisture.** The sample should be protected from exposure to the atmosphere until tested. Since the soil moisture may vary throughout the year, general drainage characteristics are recorded rather than specific moisture content.

**Experience.** In addition to the analytical tests just described, which will indicate the ability of the soil to cause corrosion, notes on prior experience in the area are extremely important. In many cases, experience can yield the best predictions of soil corrosivity.

## Steel Pipe

Steel pipe applications include buried and exposed pipelines conveying water and treatment plant and process piping systems conveying water. Modern steel water pipe generally consists of a watertight steel cylinder that is lined with cement mortar or other protective lining and then coated with cement mortar or dielectric coating. The steel cylinder is the main structural element of the pipe; however, when used, the cement–mortar lining and coating also contribute to pipe stiffness. Steel pipe is assembled in the field with welded or rubber-gasketed joints. For additional information, refer to AWWA Manual M11, *Steel Pipe—A Guide for Design and Installation*. Bare steel pipe is not recommended for direct burial unless it is coated with cement mortar or dielectric coating, encased in concrete, or pressure grouted in a tunnel liner application.

The potential for external corrosion of steel pipe depends on subsurface environmental conditions. Soil chemical and physical analyses (e.g., pH, moisture content) and the presence of stray current are important factors that impact the design and operation of corrosion control measures. Soil resistivity is generally the most important parameter for judging soil corrosivity with respect to steel pipe. As a general guideline, Tables 3-2 and 3-3 summarize the extent of corrosion attack on buried bare steel pipe as related to soil characteristics and soil resistivity. Additional information on the principles of corrosion and corrosion control can be found in AWWA Manual M11. For cement–mortar-coated steel pipe, refer to the section on concrete cylinder pipe in this chapter.

## Copper Pipe

Although copper may tend to resist subsurface corrosion, there are certain soil and environmental conditions that can cause deterioration. Specific soil chemistries that may cause problems include (1) highly alkaline organic soils where the ratio of chloride and carbonate to sulfate is high; (2) elevated concentrations of organic and inorganic acids; (3) poor aeration, which supports sulfate-reducing bacteria activity; and (4) elevated chloride, sulfide, and/or ammonia concentrations. Corrosion of copper by a soil can be aggravated by the application of fertilizer or heavy lawn sprinkling, especially if the soil is poorly drained. Copper should not be embedded directly in cinders or in tidal marshes where it may be subject to attack by sulfur compounds.

Copper in contact with concrete often acts as a cathode to nearby copper exposed to soil, causing the pipe in the soil to corrode. Premature failure of the copper at the concrete–soil interface in homes constructed on concrete slabs can occur. Copper pipe should be sleeved in polyethylene as it passes through concrete.

Another hazard to underground copper is the practice of using metal water service lines as a ground for electrical systems. If copper service lines connected to nonconducting (for example, PVC or asbestos–cement) mains are used as a ground, corrosion damage can sometimes occur where current leaves the copper, even if the current is alternating. The alternating current at certain threshold voltages can be rectified (changed to direct current, which will cause corrosion) by copper oxide films on the pipe surface, under certain soil, pH, and electrical field intensity conditions.

In domestic plumbing with parallel hot and cold water piping, underground hot-water copper pipes can act as anodes relative to the cold-water copper pipes. If the two systems are electrically connected, as can occur at the hot-water heater, the hot-water

Table 3-2 Soils grouped in order of corrosive action on steel

Group I—Lightly Corrosive

Aeration and drainage good. Characterized by uniform color and no mottling anywhere in soil profile and by very low water table. Includes

1. Sands or sandy loams
2. Light, textured silt loams
3. Porous loams or clay loams thoroughly oxidized to great depths

Group II—Moderately Corrosive

Aeration and drainage fair. Characterized by slight mottling (yellowish brown and yellowish gray) in lower part of profile (depth 18–24 in.) and by low water table. Soils would be considered well drained in an agricultural sense, as no artificial drainage is necessary for crop raising. Includes

1. Sandy loams
2. Silt loams
3. Clay loams

Group III—Badly Corrosive

Aeration and drainage poor. Characterized by heavy texture and moderate mottling close to surface (depth 6–8 in.) and with water table 2–3 ft below surface. Soils usually occupy flat areas and would require artificial drainage for crop raising. Includes

1. Clay loams
2. Clays

Group IV—Unusually Corrosive

Aeration and drainage very poor. Characterized by bluish-gray mottling at depths of 6–8 in. with water table at surface or by extreme impermeability because of colloidal material contained. Includes

1. Muck
2. Peat
3. Tidal marsh
4. Clays and organic soils
5. Adobe clay

Table 3-3 Relationship of soil corrosion to soil resistivity

| Soil Class | Description | Resistivity, *Ω-cm* |
|---|---|---|
| 1 | Excellent | 10,000–6,000 |
| 2 | Good | 6,000–4,500 |
| 3 | Fair | 4,500–2,000 |
| 4 | Bad | 2,000–0 |

pipes can experience accelerated corrosion by thermogalvanic action. This can be overcome by using an isolation union between the two lines.

## Concrete Cylinder Pipe

Concrete cylinder pipe is a general designation given to pipe manufactured with a watertight steel cylinder and reinforcing or prestressing wire, all embedded in a

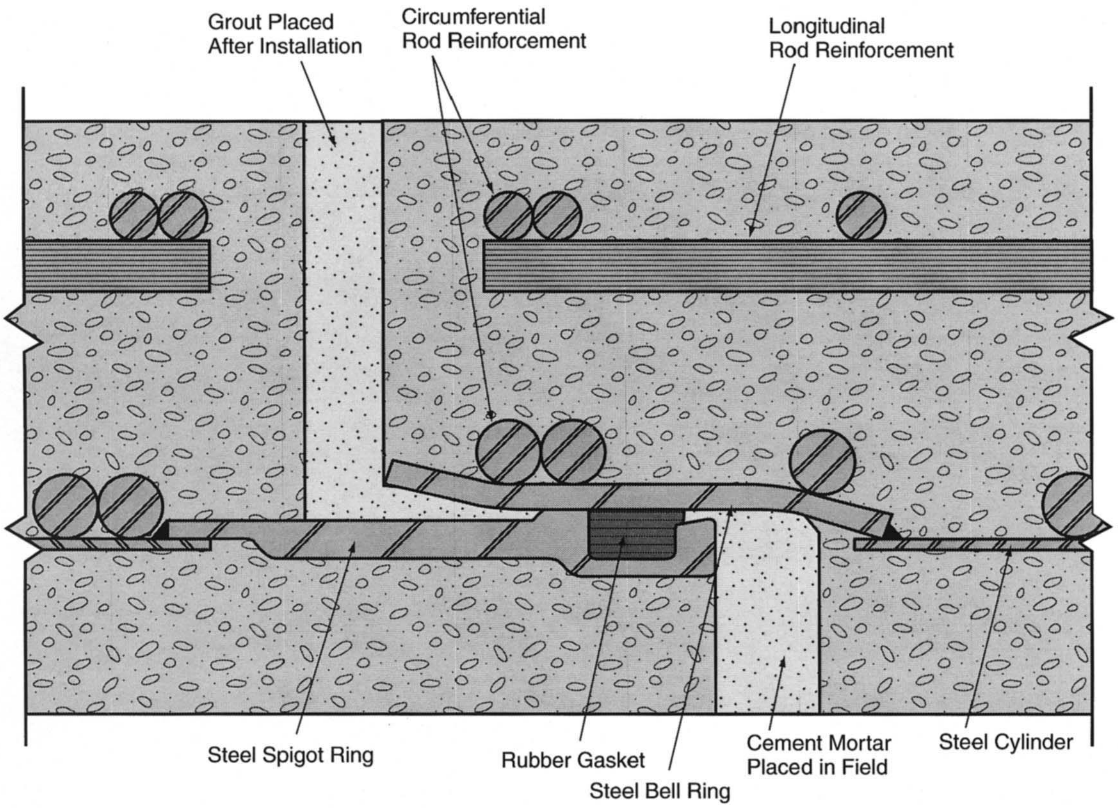


Figure 3-5 Reinforced concrete cylinder pipe (AWWA C300-type pipe)

cement-rich concrete or mortar encasement. There are presently three types being produced in the United States and Canada: reinforced concrete cylinder pipe (Figure 3-5), prestressed concrete cylinder pipe (Figures 3-6 and 3-7), and bar-wrapped concrete cylinder pipe (Figure 3-8). These types are described in detail in AWWA C300, *Standard for Reinforced Concrete Pressure Pipe, Steel-Cylinder Type*; AWWA C301, *Standard for Prestressed Concrete Pressure Pipe, Steel-Cylinder Type*; and AWWA C303, *Standard for Concrete Pressure Pipe, Bar-Wrapped, Steel-Cylinder Type.*

Concrete cylinder pipe has demonstrated consistent long life when properly installed in most natural environmental conditions. This is attributable to the protection portland cement affords embedded steel. The hydrated cement is chemically basic, having a pH of about 12.5. At this pH, an oxide film forms on the embedded steel surfaces, which passivates the steel. The passivated steel will not corrode unless a corrosion cell condition is created.

Because of the passivating effect, the potential between uncorroded steel encased in mortar or concrete and a copper–copper sulfate reference electrode (CSE) is normally between 0 mV and –300 mV. The potential of buried bare or organically coated steel or of corroding steel encased in mortar or concrete will be substantially more negative. This difference in potential between corroding and noncorroding steel can be useful in monitoring for possible corrosion activity.

In the majority of environments, no additional protective requirements are necessary for concrete cylinder pipe. However, there are unusual circumstances where precautionary measures should be taken to ensure pipeline integrity. These circumstances include (1) high chloride environments, which can depassivate steel; (2) stray

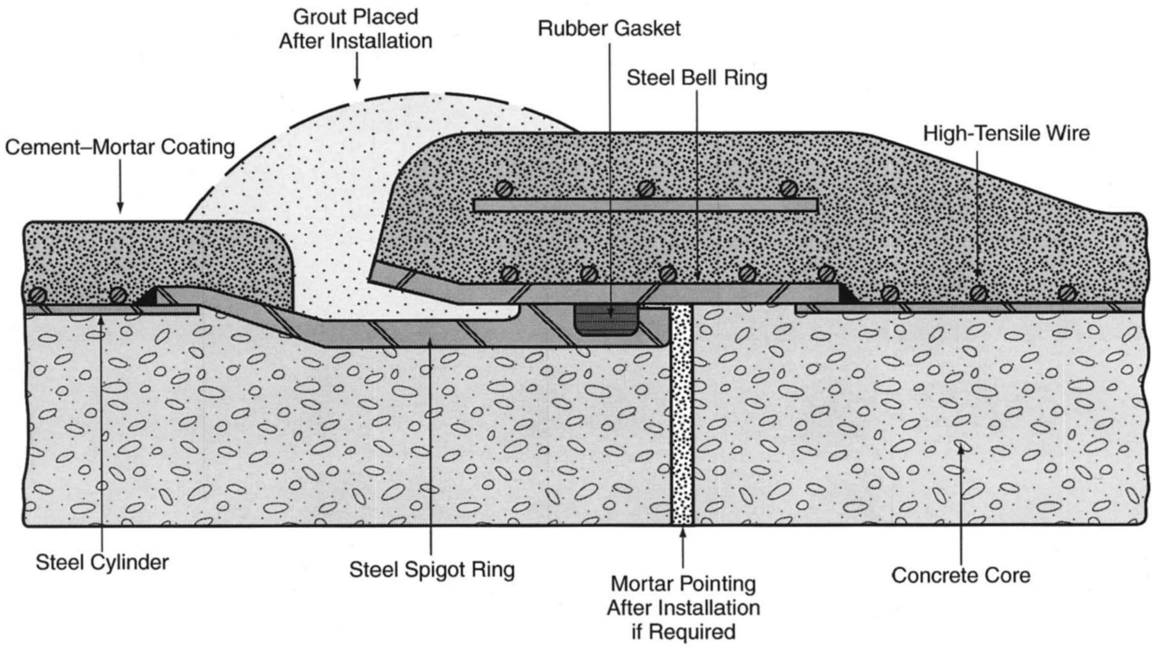


Figure 3-6 Prestressed concrete-lined cylinder pipe (AWWA C301-type pipe)

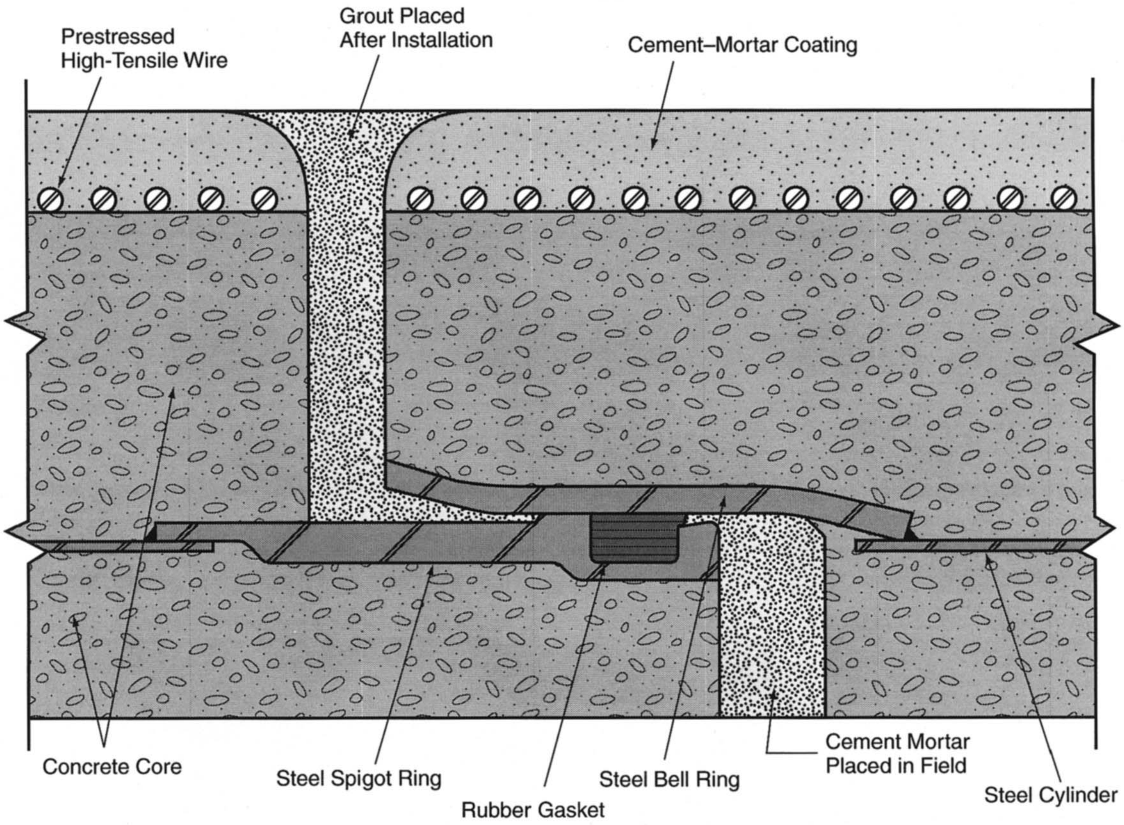


Figure 3-7 Prestressed concrete embedded cylinder pipe (AWWA C301-type pipe)

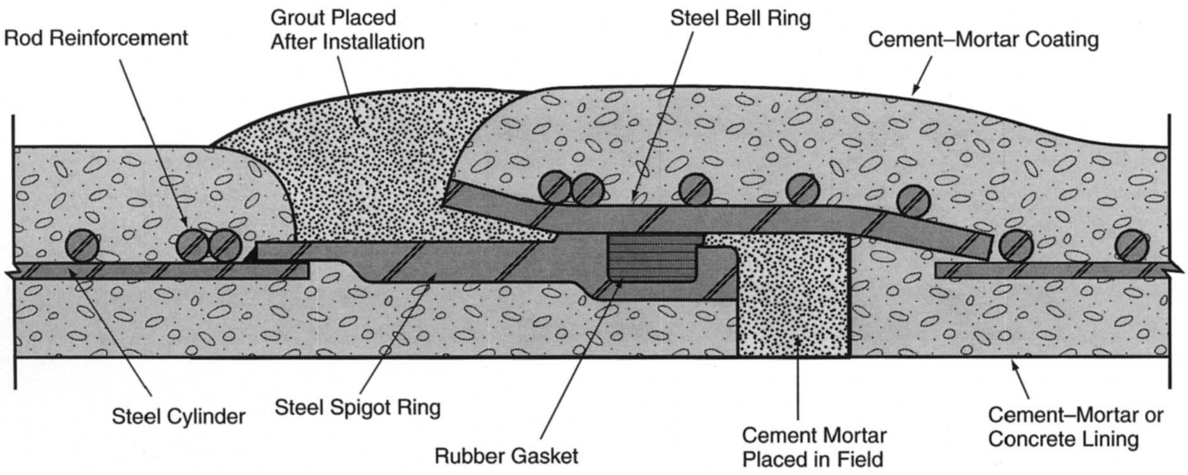


Figure 3-8 Bar-wrapped concrete cylinder pipe (AWWA C303-type pipe)

direct current interference from man-made structures; (3) high sulfate, severe acid, or aggressive carbon dioxide conditions, which can chemically attack the concrete or mortar coating; and (4) atmospheric exposure, which can deteriorate the coating. Each of these conditions is discussed in the following sections. Protective measures for these environmental conditions are more fully discussed in the AWWA Manual M9, *Concrete Pressure Pipe.*

**Chlorides.** The breakdown of passivation and possible steel corrosion can occur in sound concrete only if certain negative ions (anions) are present at the steel surface. The only anion that causes practical concern is the chloride ion. When exposed to a high concentration of chloride ions and oxygen, steel encased in concrete will corrode. The threshold chloride ion concentration required at the steel surface to initiate corrosion is quite high—about 0.02 mol/L (approximately 700 mg/L). However, in the absence of impressed (externally generated) voltages, oxygen must be replenished at the steel surface to sustain corrosion. In high-chloride environments such as continuously submerged ocean outfalls (approximately 20,000 mg/L chloride), concrete cylinder pipelines do not experience damaging corrosion of embedded steel. This is due to the extremely low rate of oxygen diffusion through the saturated mortar coatings.

Concrete cylinder pipelines buried in high-chloride soil environments must be evaluated differently from those continuously submerged in seawater. In soils that do not become totally dry in the pipe zone, such as cohesive soils, the mortar or concrete exterior will remain moist, limiting the access of oxygen to the encased steel. If the chloride ion concentration in these soils exceeds 400 ppm and soil resistivity, as measured in the maximum natural moisture state, is lower than 1,500 Ω-cm, it is prudent to apply additional protection.

**Cathodic interference.** The section on stray direct current at the end of this chapter covers evaluation of the environment for corrosive conditions that could result from interfering direct current in the area of the pipeline.

**Sulfate soils.** Soils containing elevated concentrations of sodium, magnesium, and calcium sulfates are designated sulfate soils (often incorrectly termed alkali soils) and are chiefly found in parts of western Canada and the West and Southwest of the United States. Under certain circumstances, these soils can be aggressive to concrete structures, particularly those in contact with the soil but with partial atmospheric exposure. Such installations can result in the accumulation of high sulfate concentrations in the concrete or mortar due to capillary action and evaporation. Completely buried concrete pipelines are not subject to this type of sulfate buildup and have exhibited excellent sulfate resistance. This is attributed primarily to the high cement content, averaging in excess of 10 sacks (940 lb [430 kg]) per cubic yard for mortar coating.

**Acidic soils.** Significant chemical attack of concrete cylinder pipe in acidic soils is extremely rare, usually occurring only in unnatural soils affected by contamination, such as cinders, mine wastes, or industrial dumps. Acidic conditions in natural soils are usually caused by milder, less aggressive acids formed by decaying vegetation. The effect of acidic soils on pipelines installed in low-pH conditions depends on the extent to which acidic conditions at the pipe surface can be replenished by groundwater movement. Generally speaking, no problems will occur in soil having a pH of 4 or higher where there is little groundwater movement with respect to the pipe, such as in fine-grained silts or clay. Under these conditions, the soil water at the pipe surface is neutralized by the alkalinity in the concrete or mortar. Where pH values below 5 are encountered and where considerable movement of groundwater with respect to the pipe is anticipated, such as granular soils, the total acidity should be measured to determine if supplemental protection is necessary.

**Aggressive carbon dioxide.** Carbon dioxide and moisture react with mortar or concrete to produce calcium carbonate, which has a lower pH than calcium hydroxide. This process, called carbonation, is usually limited to a thin exterior surface layer on concrete pipe due to the formation of the relatively insoluble calcium carbonate blocking further penetration of carbon dioxide. This surface carbonation is not detrimental to the pipe. Penetrating carbonation can occur under certain conditions and lead to corrosion of reinforcing steel due to the lowering of the pH of the protective mortar or concrete in contact with the reinforcing steel. Carbon dioxide generation in the soil due to decaying vegetation or geothermal activity combined with relatively soft groundwater and highly permeable soil can lead to penetrating carbonation. If these conditions are suspected, testing of groundwater for aggressive carbon dioxide is recommended. When the performance history of existing buried concrete structures or a current soils and groundwater analysis indicate a potential problem, supplemental precautions should also be considered.

**Atmospheric conditions.** Although concrete cylinder pipe is normally buried belowground, it occasionally becomes necessary to make an aboveground installation. The atmospheric environment is drastically different from buried conditions. Atmospheric conditions can bring alternate wetting and drying, rapidly changing temperatures between night and day, possible freezing and thawing cycles, and exposure to carbon dioxide. These exposure conditions over the life of the pipe can lead to deterioration of the protective concrete or mortar pipe exterior. In general, the conditions associated with atmospheric exposure can be expected to reduce pipe life unless additional protective measures are taken.

## Asbestos–Cement Pipe

Asbestos–cement (AC) pipe is available in two basic types, which are distinguished by the free lime content of the pipe. Type I pipe has no limit on uncombined calcium hydroxide; type II pipe has 1 percent or less uncombined calcium hydroxide.* In the United States, only type II AC pipe has been produced for the past several decades. In addition to asbestos fiber and portland cement, type II pipe contains approximately

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*Tests for uncombined calcium hydroxide are made in accordance with ASTM C500, available from the American Concrete Institute, PO Box 19150, Redford Station, Detroit, MI 48219.

30 percent finely ground silica. The curing process is completed in high-pressure steam autoclaves, where the temperature is approximately 300°F (150°C). The series of compounds known as hydrogarnets, which result from steam curing of cement products, are very stable and highly resistant to the action of sulfate solutions.

Guidelines for the use of AC pipe under various soil conditions are found in AWWA C400, *Standard for Asbestos–Cement Pressure Pipe, 4 In. Through 16 In. (100 mm Through 400 mm), for Water Distribution Systems*; AWWA C402, *Standard for Asbestos–Cement Transmission Pipe, 18 In. Through 42 In. (450 mm Through 1,050 mm), for Water Supply Service*; AWWA C403, *Standard for the Selection of Asbestos–Cement Transmission Pipe, Sizes 18 In. Through 42 In. (450 mm Through 1,050 mm), for Water Supply Service;* and ASTM C500, *Standard Methods for Testing Asbestos–Cement Pipe*. These guidelines establish parameters that are intended to define conditions where indefinite life expectancy can be anticipated.

Table 3-4 shows guidelines for the use of AC pipe in acidic soils based on minimum pH factors alone. AC pipe may or may not perform satisfactorily in acid soil environments having pH values below those listed in this table. To determine the suitability of AC pipe in soils having lower pH values, each situation should be evaluated individually, taking into consideration all aspects of the soil environment that affect corrosiveness to AC pipe.

Table 3-5 classifies aggressiveness to AC pipe of soluble sulfates in water and soils. Type I AC pipe will be attacked to various degrees by all but the nonaggressive levels of sulfate concentrations in waters and soils. Type II AC pipe is resistant to all levels of soluble sulfates.

## Thermoplastic Pipe

Polyvinyl chloride (PVC) and polyethylene (PE) are the thermoplastic materials most commonly used in water distribution. These materials do not corrode in the sense that

Table 3-4 Guidelines for use of AC pipe based on pH of acidic soils

| | Minimum pH of Acidic Soils When Using AC Pipe | |
|---|---|---|
| Water Conditions Within Soil Environment | Type I | Type II |
| Essentially quiescent | 5.0 | 4.0 |
| Mildly fluctuating | 5.5 | 5.0 |
| Rapidly moving or grossly cyclic | 6.3 | 5.5 |

*Source:* AWWA C403

Table 3-5 Corrosion guidelines for AC pipe for soluble sulfate in water and soils

| Sulfate Aggressiveness | $SO_4$ in Soil, *ppm* |
|---|---|
| Nonaggressive | 1,000 and less |
| Mildly aggressive | 1,000 to 2,000 |
| Moderately aggressive | 2,000 to 20,000 |
| Highly aggressive | 20,000 and above |

*Source:* AWWA C403

metals do. Being nonconductors, they are immune to corrosion by galvanic or electrochemical effects. They are also unaffected by polar active materials, such as aqueous acids, bases, and salts. Consequently, linings, coatings, and cathodic protection are not required with thermoplastic piping. However, certain substances that are seldom encountered in municipal water distribution environments can adversely affect thermoplastic pipe's structural properties through direct chemical attack, solvation, or environmental stress cracking. Pipeline contact with such substances can occur in instances of subsurface contamination by leaking gasoline storage tanks, solvents, aromatic hydrocarbons, ketones, and certain oils. The nature and extent of their effect depend on the following:

- Type or nature of the chemical(s) present
- Concentration of the chemical(s)
- Duration or persistence of exposure
- Temperature
- Pipe material, i.e., PVC or PE.

Possible effects range from slight swelling with little loss of properties to severe softening and significant loss of tensile strength. Some PE materials are also subject to environmental stress cracking when simultaneously subjected to stress and certain organic liquids. AWWA standards for PE pipe prohibit the use of those grades of PE. PVC pipe intended for aboveground applications should be protected from ultraviolet radiation by painting, wrapping, or coating the pipe. Alternatively, PVC pipe may be formulated with special additives for aboveground applications (e.g., PVC aboveground irrigation pipe).

When thermoplastic pipe is considered for use with harmful chemical reagents or solvents, the pipe's suitability for that exposure must be evaluated. For more information regarding PVC pressure pipe's environmental resistance, consult AWWA Manual M23, *PVC Pipe—Design and Installation.* Information on the environmental resistance of PE pipe can be obtained from the Plastics Pipe Institute.*

## STRAY CURRENTS

Direct-current electricity flowing through the soil near a metal pipeline or structure can cause electrolytic corrosion of the metal or alloy. The electricity is referred to as stray current because it has strayed away from the path intended for it in the circuit where it originated. Stray current is primarily a problem for long, electrically continuous pipelines, which can form a lower resistance pathway for the current than is found in its original circuit. Electrically segmented pipelines (those using rubber-gasketed joints that are not bonded) are usually not vulnerable to stray-current corrosion, unless near the direct current source.

When planning a new pipeline, or if stray direct current is suspected of causing corrosion, the first step in analyzing the problem is to review the possible sources of direct current. Common sources include impressed-current cathodic-protection systems, direct-current powered transit systems, arc-welding equipment, and direct-current transmission systems. The effects from cathodic protection do not vary because cathodic protection current is constant. Effects from most other sources vary with operation. If a local corrosion-control coordinating committee exists, its members are usually well informed on such sources. Information on such committees is available from the National Association of Corrosion Engineers (NACE) [http://www.nace.org]. If there is no such committee, consult other utility operators.

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*Plastics Pipe Institute, 1825 Connecticut Avenue NW, Suite 680, Washington, DC 20009.

Several electrical tests are commonly used for the analysis of stray current in the field. The tests measure a voltage differential or line current. The pipe-to-soil (structure-to-environment) test measures the voltage between the pipe and the soil, using a reference electrode. The current-span (IR-drop, also known as voltage drop) test measures the voltage between two points on the pipeline. The ground-voltage gradient test measures the voltage between two points in the soil. When test leads are placed at appropriate intervals along the pipeline, these tests allow the line to be monitored both for the existence of environmental stray currents and, to some extent, for the existence of active corrosion. The tests and observations are best applied to long, electrically continuous metal pipelines. Bonding of rubber-gasketed joints may be necessary if the line is to be monitored for possible stray current or is cathodically protected.

The following sections briefly describe each test and its interpretation. Note that any attempt to monitor a pipeline requires detailed records showing the location of outlets, connections to other lines, pipeline appurtenance structures (such as air valves and manholes), and proximity to foreign lines or structures that could influence monitoring data.

## Pipe-to-Soil Potential

Pipe-to-soil potential (also called structure-to-environment potential) is the potential between the metal and a reference electrode placed in contact with the earth. The reference cell is one-half of a battery. In the commonly used copper–copper sulfate reference electrode (CSE), the "half-cell" consists of a copper rod in a saturated solution of copper sulfate crystals. The other half of the cell is the metal in the soil electrolyte.

The reference cell has a stable, constant potential against which the voltage of another metal can be measured, analogous to measuring elevation with reference to sea level. When the potential between a pipe and reference electrode in contact with the earth is measured, the potential includes not only the voltage between the pipe and reference cell but also IR-drop voltages created by currents flowing through the resistance of the earth. This measurement is the most useful test in evaluating stray-current effects and cathodic protection effectiveness.

When a pipe is connected to the positive terminal of a digital voltmeter and the reference cell is connected to the negative terminal, the meter will give a negative reading, indicating that the pipe is negative to the reference electrode. A negative or minus sign should be placed in front of the voltage reading. Note, however, that an analog-type voltmeter or potentiometer would read backward with these connections; and, the reference cell must be hooked to the positive terminal and the pipe to the negative terminal so that the needle will read upscale. Again, a negative sign must be added to indicate that the pipe is negative to the reference cell even though the analog meter has moved in a positive direction. Figure 3-9 illustrates the arrangement for measuring pipe-to-soil potential with a digital voltmeter.

The best type of connection is an insulated test lead, brazed or thermite-welded to the pipe. However, a connection may be made to a valve, blowoff, or other accessible appurtenance, provided that it is electrically continuous with the pipe.

Pipe-to-soil potentials measured with the reference electrode placed at intervals along and over the centerline of an electrically continuous pipeline may vary, indicating anodic (corroding) and cathodic areas of the pipe. Readings taken with the reference electrode offset from the centerline of the pipe can also help locate anodic areas. Offset readings identical to the pipe alignment readings indicate neither cathodic nor anodic conditions, and if consistent, rule out the existence of stray current.

If pipe-to-soil potentials become less negative as a reference cell is *moved closer* to the pipe, then current is flowing toward the pipe and the pipe is cathodic. If pipe-to-soil potentials become less negative as the reference cell is *moved away* from the pipe, then the pipe is anodic and tends to corrode. This is true for natural galvanic corrosion cells

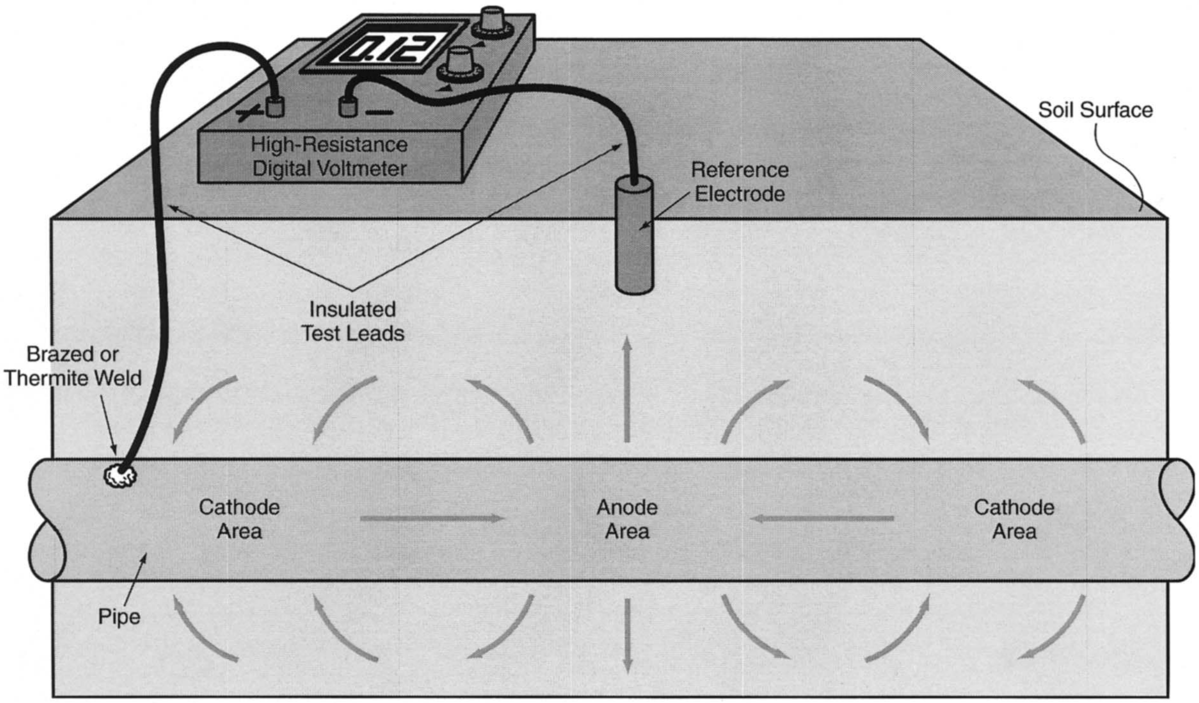

Figure 3-9 Testing for pipe-to-soil potential

such as between dissimilar metals and alloys or anodic and cathodic areas on the same metal or alloy and where the pipe is under cathodic protection. But, if the pipe is losing current due to stray current, the pipe-to-soil potential close to the pipe will be less negative (and may even go positive) than potentials farther from the pipe.

## Current Span and Line Current

Line current measurements are useful for identifying stray or long-line currents on a continuous pipeline and for locating suspected corrosion areas. Line current can be determined by measuring the voltage (IR drop) between two points on a pipeline, then calculating the amplitude of current required to produce that potential in a line of the given size and material. The test procedure uses a high-resistance voltmeter (with millivolt ranges), with the terminals connected to test leads from the pipe. For most steel pipe with welded joints, current flow in amperes can be determined by the formula

$$I = KV \tag{3-1}$$

Where:

$I$ = current flow between the two points (A)
$K$ = 4.0 $W/L$, a conversion factor indicating the resistance of the pipe (A/mV)
$W$ = the weight-per-length of the steel pipe (lb/ft)
$L$ = length of the span (ft) (calculation of $K$ assumes welded pipe joints, steel resistivity of 15.5 Ω-cm, and steel density of 490 lb/ft$^3$)
$V$ = measured voltage differential (mV)

Similar calculations can be made for other types of metallic pipelines.

The test span can be calibrated by causing a known direct current to flow across the span (using test points outside the two IR span test points) to obtain the conductivity of the span, in amperes/millivolt.

Similarly, current in a span can be determined by applying a direct current opposite to the stray current between two test points, then adjusting the applied current until the measured potential between the test points is zero. The applied countercurrent is equal to the current flowing along the pipe. A series of current-span tests along a pipeline can help locate areas of discharge or assimilation of stray current.

Line currents can also be measured by means of a clamp-on ammeter, using clamps sized to fit the pipe. Clamps can be manufactured for virtually any size pipe. These are most useful above grade or in vaults where the clamp can be attached without excavating the full diameter of the pipeline.

## Ground Voltage Gradients

Testing ground voltage gradients helps to determine whether there is current flowing through the soil in the vicinity of an existing or proposed underground structure. It also can indicate the direction of any current flow and thus help locate its source. When plotted along the pipe alignment, results of the tests may even be helpful in locating suspected anodic areas on a pipeline.

Ground voltage gradients are tested with a high-resistance millivolt meter and two matched copper–copper sulfate half-cells. Half-cells may be checked by placing them side by side in the soil surface. A zero millivolt reading shows that they are properly matched.

With the half-cells placed in the soil surface at a selected spacing, any millivolt potential is recorded. If such a potential exists, presence of earth current is implied. Measuring the gradient is accomplished by making a series of such readings in a straight line. "Leap frogging"—leaving one half-cell in place and carrying the other past it to a new location of equal spacing along the alignment of the study—makes the test proceed more quickly, but care must be taken to reverse the sign for each new reading. Significant variations in the ground voltage may indicate anodic and cathodic sections of the pipeline. The test can also confirm the existence of areas of concern that were determined previously using pipe-to-soil tests.

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AWWA C400, *Standard for Asbestos–Cement Pressure Pipe, 4 In. Through 16 In. (100 mm Through 400 mm), for Water Distribution Systems*. American Water Works Association: Denver, CO.

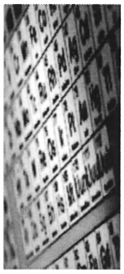
AWWA C402, *Standard for Asbestos–Cement Transmission Pipe, 18 In. Through 42 In. (450 mm Through 1,050 mm), for Water Supply Service*. American Water Works Association: Denver, CO.

AWWA C403, *Standard for the Selection of Asbestos–Cement Transmission Pipe, Sizes 18 In. Through 42 In. (450 mm Through 1,050 mm), for Water Supply Service*. American Water Works Association: Denver, CO.

AWWA Manual M9, *Concrete Pressure Pipe.* American Water Works Association: Denver, CO.

AWWA Manual M11, *Steel Pipe—A Guide for Design and Installation.* American Water Works Association: Denver, CO.

AWWA Manual M23, *PVC Pipe—Design and Installation.* American Water Works Association: Denver, CO.



## *Chapter* 4

# Corrosion Protection of Buried Pipelines

Where tests and observations indicate that corrosion will be a problem in a new or existing installation, steps must be taken to reduce the severity of the corrosion or eliminate it entirely. A variety of methods and combinations of methods are available for corrosion control. All are based on the principle, discussed in detail in chapter 2, that four elements are required to support corrosion—an anode, a cathode, an electrolyte, and a return current path. If any one of these elements can be eliminated, deactivated, or isolated from the others, then corrosion will be prevented.

This chapter discusses several corrosion-control systems used by water utilities, including coatings, cathodic protection, polyethylene encasement of ductile iron, selection of corrosion-resistant materials, and environmental alteration. The operation, advantages, and disadvantages of each method are covered.

After completing this chapter, the reader should be able to

- understand the function of coatings in the prevention of corrosion;
- know the basic procedures used for cathodic protection;
- know how to avoid combinations of metals or alloys that cause bimetal corrosion cells;
- have an understanding of electrolyte (environment) alteration for corrosion prevention; and
- recognize specific precautions required for certain pipe materials in certain environments.

## COATINGS

Coatings control corrosion by creating a barrier between a metal and its environment, the potentially corrosive electrolyte. A coating's effectiveness depends on its degree of integrity (freedom from holes called holidays), its ability to bond to metal, and its ability to insulate against the flow of electrical current. A coating material must also be economically feasible.

## General Properties of Coatings

Coatings were used in early attempts to control corrosion—examples include coal-tar pitch for coating gray-iron and steel pipes and the use of various paints to preserve wood structures. Yet even with the large number of coating materials now available, the perfect coating does not exist. Although coatings dramatically reduce corrosion in water utility structures, the user must be aware of certain possible shortcomings:

- Factory-applied coatings may be damaged during shipping, handling, storage, or construction. It is often possible to field-repair damaged coatings, but some factory-applied coatings cannot be repaired to their original quality.
- If a pinhole or holiday exists in a bonded organic coating in a corrosive environment, a concentration cell may develop that will undermine the coating and cause corrosion similar to crevice corrosion.
- If a metal with a bonded organic-type coating is under cathodic protection, excessive current can cause coating disbondment.

For these reasons, it is generally accepted that bonded organic coatings in corrosive environments should be supplemented by cathodic protection. The properties of coatings and cathodic protection systems are synergistic: coatings greatly reduce the cost of the cathodic protection system, while cathodic protection substantially extends the useful life of the coating. In most instances, lower maintenance and life-cycle costs are the result.

## Specific Properties of Common Coatings

The following paragraphs describe some commonly used coating materials. The list is not complete, and additional materials are constantly being developed.

**Asphalt.** The predominant ingredient of asphalt coatings is bitumen. Most asphalt is a petroleum distillate; however, natural asphalts, such as gilsonite, are sometimes used in combination with petroleum asphalts to enhance certain physical properties.

**Coal-tar epoxy and coal-tar urethane.** Both coal-tar epoxy coatings and coal-tar urethane coatings are combinations of coal tar and chemicals that yield increased qualities of toughness, resistance to weathering and aging, and electrical resistance. These materials are excellent external coatings.

**Coal tar (thermoplastic).** Containing primarily coal-tar pitch, both hot- and cold-applied coatings are available. Coal tar is an effective coating material when properly applied with adequate thickness.

**Concrete and cement mortar.** Both concrete and cement mortar are used for coating tanks and pipes. Concrete has the advantage that minor cracking can heal in water exposure. (For further information, review the discussion of concrete cylinder pipe in chapter 3.)

**Epoxy.** A wide range of epoxy resins with varying properties is used as coatings. In general, they form good, continuous coatings, offering good resistance to alkalies, salts, oils, abrasion, weathering, and aging, and have high electrical-insulating ability. Adhesion is good on both metal and concrete. High-build epoxies have been especially useful in the protection of water treatment plant equipment and wells.

**Fluorocarbons.** Often used as thin-film coatings, fluorocarbons offer resistance to chlorine, bromine, and iodine, but in severe exposures may be vulnerable to fluorine. They may find use in atmospheric exposures in water treatment plants where free chlorine is present. Application requires skill and experience, and cost is significant.

**Glass (ceramic).** Properly applied, glass coatings offer superior service in water exposures. Glass coating is a shop procedure requiring very high temperatures.

The temperature is so great that care must be taken not to alter the metallurgical character of the metal or alloy. Glass coatings are expensive but may be cost-effective for special applications.

**Metallic coatings.** Zinc, nickel, tin, and cadmium are examples of metallic coatings. With the exception of zinc and cadmium, which are sacrificial metals, their chief function is to serve as a physical barrier between the protected metal and the environment. Unlike organic coatings, they do not act as a dielectric. Metal coatings are applied by electroplating, flame spraying, hot dipping, or vapor deposition. Galvanized (zinc-coated) pipes and other equipment have been used extensively in water systems, especially in service piping. If a corrosion cell develops in a galvanized pipe, the zinc, because of its position in the galvanic series, becomes anodic and tends to create cathodic (noncorrosive) conditions at the attack site. However, experience has shown that such protection is short-term at best.

**Polyesters.** Although they are resistant to many chemicals and to moisture, polyesters generally must be used with reinforcement because of their brittle nature. Adherence to metal is not good unless the metal is deeply etched or blasted. Polyester coatings are not expected to find significant application in the water supply field.

**Polyether.** Application requirements limit the use of chlorinated polyether in water utility service. The base resin is resistant to aging, abrasion, weather, and many chemicals. The material must be applied at elevated temperatures, then quenched in cold water. Currently, there is no solvent available that allows application at room temperature.

**Polyethylene.** Low- and high-density polyethylene (PE) resins are available. Although the base resin is lower in cost than most other coating materials, application procedures and service limitations may offset the higher cost of other coatings. In general, best results are obtained when the resin is applied to a metal or alloy at elevated temperatures or flame sprayed. The coating is not entirely homogeneous and, therefore, its properties of resistance are not precise. Polyethylene also is used as a bonded or loose wrapping material for pipe in corrosive soil environments. Its dielectric strength is excellent, as is its resistance to aging.

**Polymer concretes.** Polymer concretes provide higher resistance to penetration by chlorides through polymer impregnation of finished concrete with specialized equipment.

**Polyvinyl chloride.** Polyvinyl chloride (PVC) coatings are a versatile group of materials offering good properties of resistance and dielectric strength. They are applied by dipping, spraying, brushing, or roller coating but usually require that the metal be blast-cleaned and primed. PVC is also used for tape coatings, which offer good resistance to aging and have good dielectric strength.

## CATHODIC PROTECTION

Cathodic protection is a system for reducing corrosion of a metal structure by turning the entire structure into the cathode of a galvanic or electrolytic corrosion cell. Direct electrical current, either generated by the galvanic cell or fed into the electrolytic cell from an external source, flows into the protected structure, overcoming any currents that might be created by naturally occurring corrosion cells in which the structure would be the anode. Since current does not flow from the structure to the electrolyte, corrosion cannot occur. The cathodic protection methods discussed in this section can be used for steel (dielectric or concrete-coated), cast-iron, ductile-iron, copper, and concrete cylinder pipe (reinforced, prestressed, and pretensioned).

To form the protective galvanic or electrolytic cell, the same four elements are required as for a naturally occurring corrosion cell: an anode, a cathode, a conductive electrolyte, and a return current path. The cathode is the protected structure itself, which must be electrically continuous to ensure complete protection. The conductive

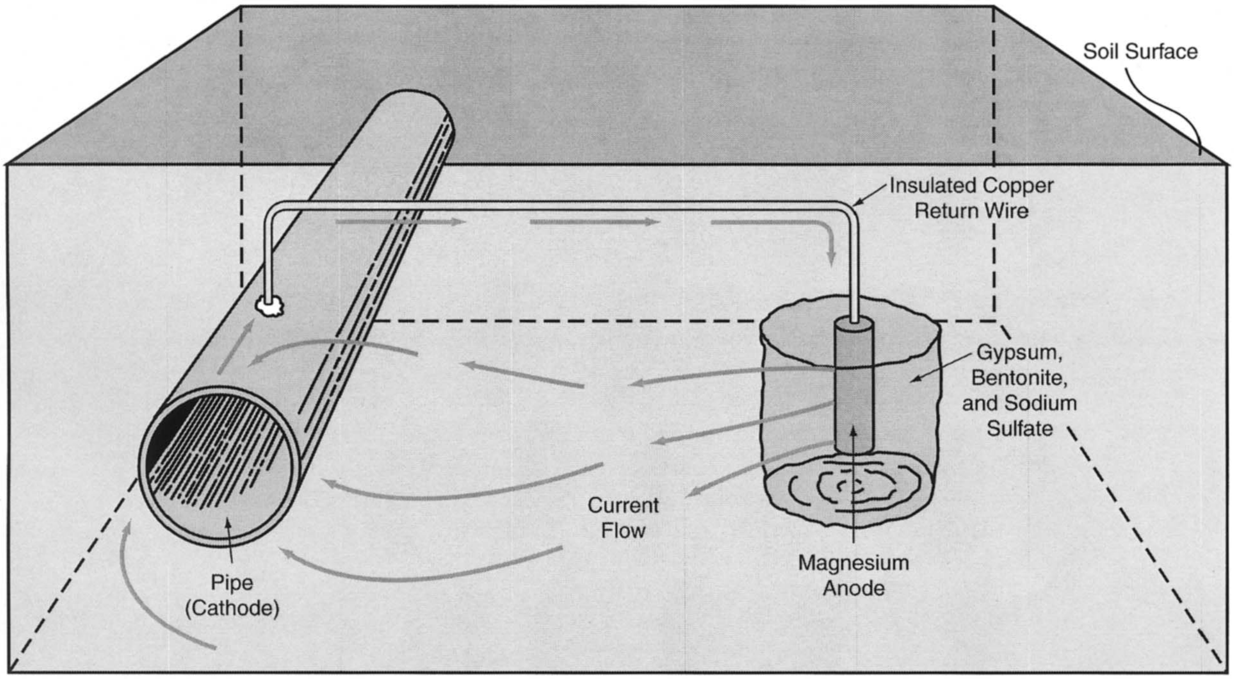


Figure 4-1 Cathodic protection system (galvanic cell using sacrificial anodes)

electrolyte is the corrosive soil environment. The anode and the return current path are added, as shown in Figure 4-1. To create the galvanic cell, appropriate anodes are selected from the galvanic series to generate the needed current. To create an electrolytic corrosion cell, an external direct current source is used. In either case, the installed anodes are bars or rods of metal that are intended to corrode. Anodes may require replacement after several years of service.

A qualified corrosion engineer should conduct the design of effective, economically feasible cathodic-protection systems. The examples in this chapter are not intended as a reference for design, but rather to provide an overview of processes and equipment and illustrate conventional system designs. Details such as anode size, anode material, and terminal box design will vary considerably from one installation to another.

NOTE: Systems that incorporate cathodic protection require routine monitoring and maintenance to assure that proper protection is provided. Follow the manufacturer's recommendations regarding this issue.

## Sacrificial Anode Systems

Cathodic protection installations in which a galvanic cell is created are referred to as sacrificial anode systems.

**Operating principles and common uses.** The sacrificial anodes, also called galvanic anodes, are made of metals or alloys that are electronegative to the structure that must be protected—that is, they are nearer to the anodic end of the galvanic series. When inserted in the same soil as the structure and connected to it by a return current path, the sacrificial anode becomes the anode of a galvanic cell and corrodes, generating an electrical current. The structure becomes the cathode and is protected. Details of a typical sacrificial anode installation are illustrated in Figure 4-2.

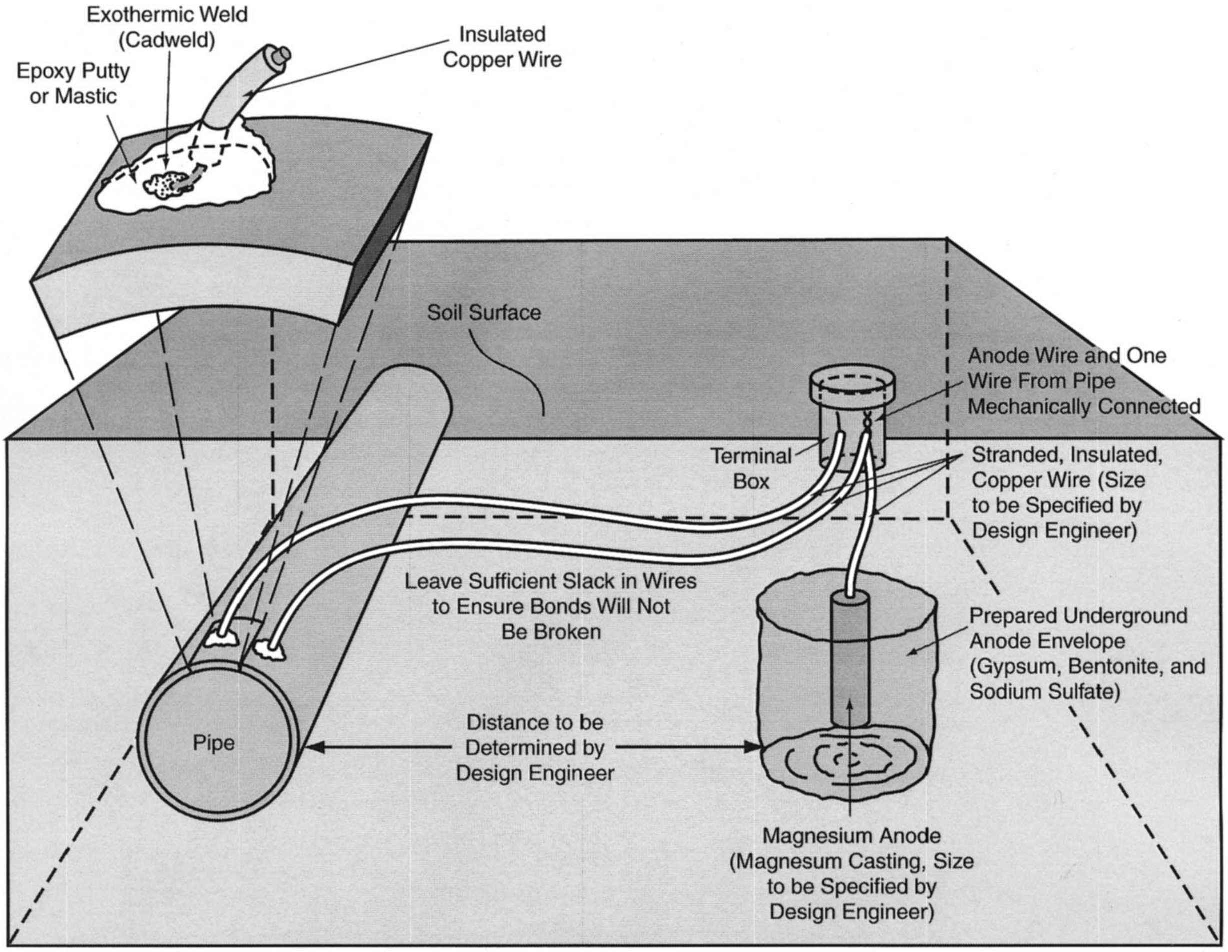


Figure 4-2 Details of a sacrificial anode installation

Sacrificial anode protection may be used selectively in "hot spot" areas that have been located by soil survey procedures. This requires that rubber-gasketed joints be electrically bonded throughout the protected area. The same protection can also be used to protect steel tanks, well casings, steel piping, and other water treatment equipment. Advantages and disadvantages of sacrificial anode systems include

**Advantages**

- No external power is required.
- Relatively low installation costs and minimal maintenance.
- Systems seldom cause interference with foreign structures.

**Disadvantages**

- Driving voltages are limited.
- Current output is limited.
- Operation is effective only in relatively low-resistivity soils.
- Anodes must be replaced frequently in high-current demand environments.

**Design and construction.** Zinc and magnesium are metals commonly used as sacrificial anodes to protect iron and steel structures. Magnesium anodes are probably the most widely used, because they create a higher cell voltage than zinc anodes. Magnesium anodes afford protection in soil with resistivities below 5,000 Ω-cm. Zinc anodes are limited to use in soils of about 1,000 Ω-cm resistivity or less. To determine the current output of a magnesium anode, the anode and correction factors must be known. Table 4-1 lists anode factors based on the required pipe-to-soil (P/S) potential.

Generally, protection is achieved with a negative potential of at least –850 mV with cathodic protection applied, measured with respect to a saturated copper–copper sulfate reference electrode contacting the electrolyte (NACE RP 169-96). An alternative measure of protection is a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte (NACE RPO 0100-2000). Current output of the anode is calculated using the following formula:

$$I = \frac{150{,}000\, fy}{P} \tag{4-1}$$

Where:

$I$ = current output (mA)
$f$ = anode factor, from Table 4-1
$y$ = correction factor, from Table 4-1
$P$ = average resistivity (Ω-cm)

For example, for a P/S potential of –0.90 V, a 17-lb magnesium anode, and an average resistivity of 1,000 Ω-cm, the anode current output would be

$$I = \frac{150{,}000 \times 1.0 \times 0.93}{1{,}000} = -140 \text{ mA} \tag{4-2}$$

The life expectancy of a sacrificial anode is inversely proportional to the current flow. The actual life varies with the materials (e.g., zinc versus magnesium), the installation, and the utilization factor (a measure of the allowable anode consumption before it is rendered ineffective, typically 85 percent). Nominal zinc anode consumption is roughly 25 pounds per amp-year while magnesium anodes are consumed at just under 10 pounds per amp year. Note that these are only rough approximations and actual consumption rates may vary significantly.

Table 4-1 Magnesium anode factors

| Magnesium* Anode Weight, *lb (kg)* | Dimensions *in.* | Dimensions *(mm)* | Anode Factor, *f* | Desired P/S | Correction Factor (Magnesium), *y* |
|---|---|---|---|---|---|
| 3 (1) | 3 × 3 × 4.5 | (76 × 76 × 144) | 0.53 | –0.70 | 1.14 |
| 5 (2) | 3 × 3 × 7.5 | (76 × 76 × 191) | 0.60 | –0.80 | 1.07 |
| 9 (4) | 3 × 3 × 13.5 | (76 × 76 × 343) | 0.71 | –0.85 | 1.00 |
| 17 (8) | 3 × 3 × 25.5 | (76 × 76 × 648) | 1.00 | –0.90 | 0.93 |
| 32 (15) | 5 × 5 × 21 | (127 × 127 × 533) | 1.06 | –1.00 | 0.79 |
| 50 (23) | 8 diameter × 15 | (203 diameter × 381) | 1.09 | –1.10 | 0.64 |

* These factors are based on typical anode dimensions.

The contact resistance of a vertically installed ground rod can be calculated as follows:

$$R_v = \frac{\rho\left(\ln\frac{8L}{d} - 1\right)}{2\pi L} \tag{4-3}$$

Where:

$R_v$ = resistance to earth (Ω)
$L$ = length of ground rod (cm)
$d$ = diameter of ground rod (cm)
$\rho$ = resistivity (Ω-cm)

Thus, it can be seen that the ground rod or chemical backfill geometry can have a great effect on the resistance. The current output is related to the resistance in accordance with Ohm's law:

$$I = E/R \tag{4-4}$$

Where:

$I$ = current (A)
$E$ = voltage (V)
$R$ = resistance (Ω)

The anode factors developed by Tefankjian (1972) are the results of the foregoing computations. For example, compare the utility of a 17-lb Galvomag magnesium anode (3 in. × 3 in. × 25.5 in.) packaged in a 6-in. × 28-in. chemical backfill with a 17-lb high-purity magnesium anode (4 in. × 4 in. × 17 in.) packaged in a 6.5-in. × 19-in. chemical backfill. The former will provide lower contact resistance (owing to its greater length) and a higher driving voltage. Thus, in accordance with Ohm's law, the magnesium anode will provide more current and hence greater protective potential.

## Impressed Current Systems

Cathodic protection systems using an external power current source are called impressed current systems, or rectifier ground bed systems.

**Operating principles and common uses.** As illustrated in Figure 4-3, impressed current systems include a rectifier unit supplying direct electrical current and a series of anodes inserted into the soil (called the ground bed). Electric current from the positive terminal of the rectifier is applied to the ground bed anodes, where it is driven (impressed) into the earth. The current travels through the earth to the protected structure. The structure carries the current to a connecting wire, which returns it to the negative terminal of the rectifier. As the current flows, the structure—acting as the cathode of the electrolytic cell—is protected from corrosion, and the anodes in the ground bed corrode.

Typically, an impressed current system is used to protect large structures or long stretches of pipeline. Advantages and disadvantages of the system include

**Advantages**

- Large driving voltages are possible.
- Higher (virtually unlimited) current levels are available.
- The system is suitable for high-resistivity soils.
- Larger structures and longer pipelines can be protected.

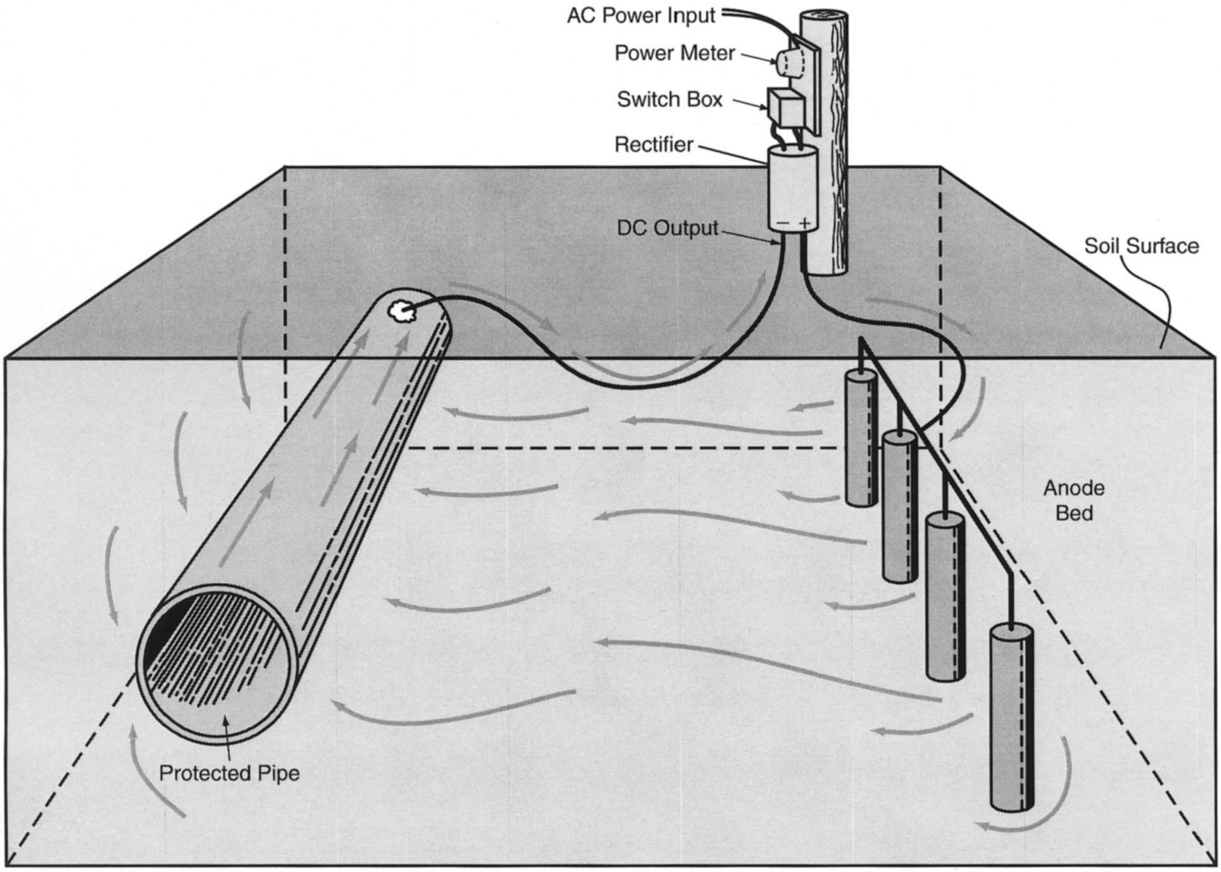


Figure 4-3 Details of an impressed current system

**Disadvantages**

- Installation costs are higher than for sacrificial anode systems.
- Maintenance and operating costs are higher than for sacrificial anode systems.
- There is a danger of damage to other structures from stray currents.

**Design and construction.** Design of an impressed current system requires that the corrosion control engineer carefully evaluate the anode materials and ground bed configuration, the current supply unit, the electrical continuity of the protected structure, the potential for stray current corrosion of nearby structures, and a number of environmental variables.

The anodes are usually composed of graphite, high-silicon cast iron, or scrap metal. There are four basic configurations of ground bed installation. In the horizontally *remote* configuration, the ground bed is placed some distance from the protected structure to effect a wide spread of current. In the *deep well* (vertically remote) configuration, anodes are placed in deep holes to spread current or to protect deep structures, such as well casings. In the *distributed* configuration (see Figure 4-3), anodes are located to protect specific structures, such as tanks, or are distributed along a pipeline. This configuration reduces interference with other underground structures and the shielding effect one structure may have for another. In the *horizontal* configuration (also called the parallel configuration), a continuous anode is installed parallel to the protected pipeline. This provides good current coverage and reduces interference with other structures.

The current supply unit, as shown in Figure 4-3, includes a 110-V AC power supply, a meter, a switch box with a circuit breaker to protect the rectifier, a step-down transformer to reduce the voltage, and a rectifying element to change the alternating current to direct current. The rectifying elements are copper oxide cells, selenium cells, or silicon diodes.

The electrical continuity of the protected structure is essential, since it acts as part of the return current path. If there is a break in the electrical continuity, perhaps at a pipe joint, the electrical driving force of the system will force the current into the soil, producing metallic corrosion at the point where the current leaves the protected structure (Figure 4-4).

Structures that lie in the area of the protected structure but are not electrically continuous with it may also be corroded by the cathodic protection currents (Figure 4-5). This problem, called stray current corrosion, is a major hazard of impressed current systems. The extent of stray current corrosion depends on the location, size, and configuration of the foreign structure. The problem may be prevented by electrically bonding the foreign structure to the protected structure. Refer to chapter 3 for a discussion of stray current monitoring, which must be integral to any cathodic protection system.

Environmental variables that must be considered when designing an impressed current cathodic protection system include

- details of the structure to be protected,
- average soil resistivity,

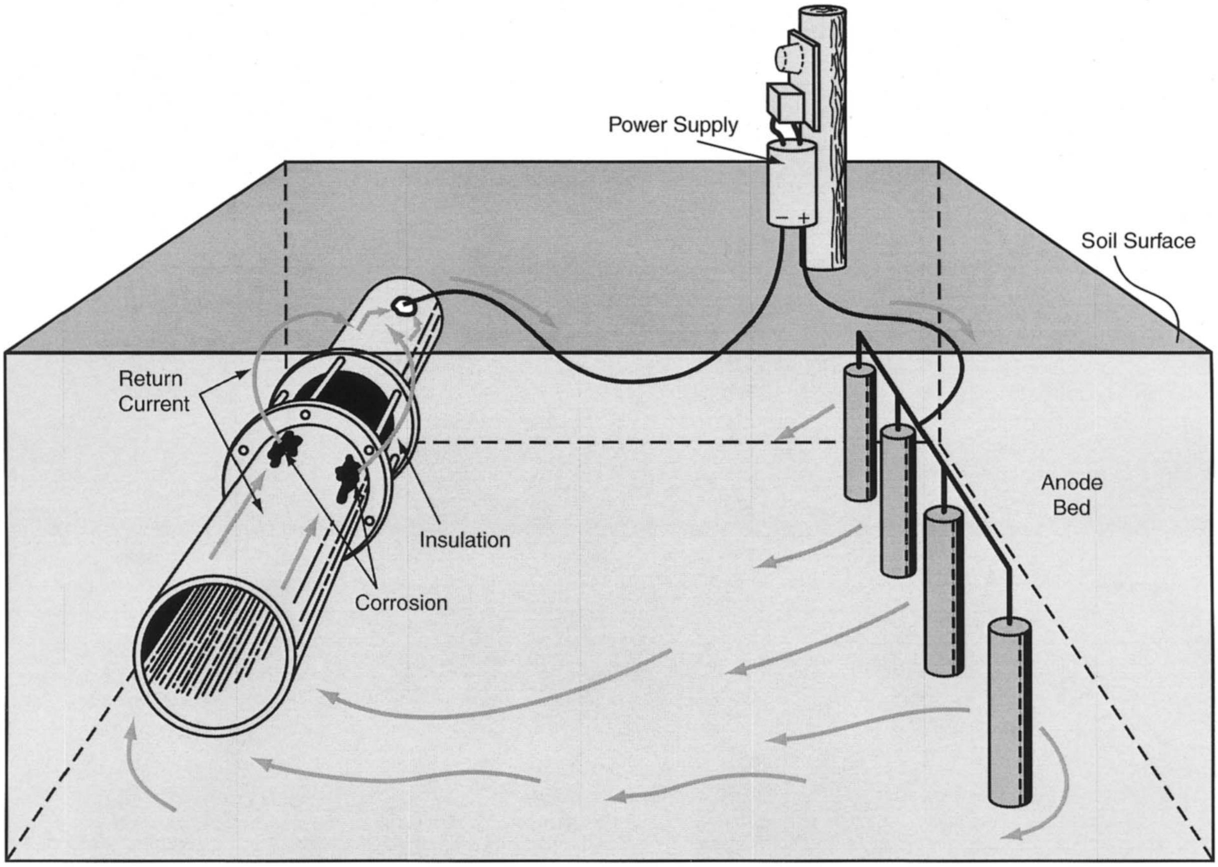


Figure 4-4 Corrosion caused by electrical discontinuity in a cathodically protected pipeline

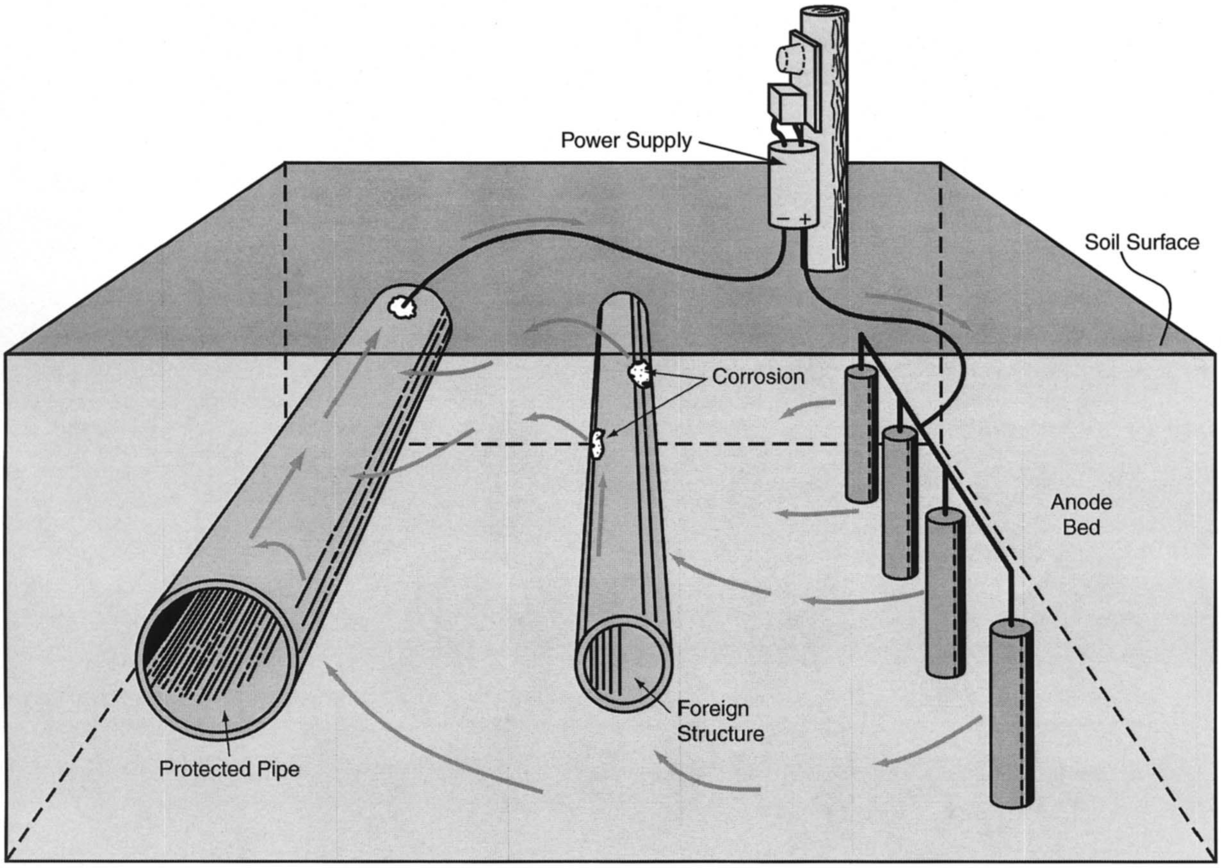


Figure 4-5 Corrosion of a metal structure in the vicinity of a cathodically protected structure

- current requirements,
- locations and types of foreign structures,
- availability of power supply, and
- property easements.

In designing a system to serve a pipeline, soil-survey data is reviewed and an area of low resistivity chosen for the anode ground bed. Once the area is selected, a current-requirement test is performed. The results of this test aid in selecting the rectifier and determining the potential effects on foreign structures. With the current requirement established, the entire system is designed to have as low a circuit resistance as feasible. Lower circuit resistance will result in lower initial and continuing power costs.

Significant contributions to circuit resistance are made by the rectifier, the earth, the anode-to-earth and structure-to-earth interfaces, and the cables connecting the rectifier to the anodes and to the structure. The anode-to-earth resistance depends on the placement, number, and spacing of the anodes. This resistance can be reduced by surrounding each anode with coke breeze. Formulas for estimating anode-to-earth resistance are available. The number of anodes can also be mathematically determined if anode-to-earth resistance, soil resistivity, anode spacing, anode length, and anode radius have been determined.

### Stray Current and Cathodic Protection Interference

When stray current from direct current sources such as electric railways or impressed current cathodic protection systems exists along the proposed right-of-way, one of the following should be implemented:

- eliminate the stray direct current if possible;
- apply a dielectric barrier to the pipe exterior; or
- make the pipeline electrically continuous and provide test stations so it can be determined if stray direct current is being picked up or discharged. If direct current is being picked up, provide the means to safely discharge it.

## MATERIALS SELECTION

Earlier chapters discussed materials and combinations of materials that are vulnerable to corrosion under certain conditions. Based on that discussion, the following rules of thumb may be helpful in reducing corrosion problems often associated with water utility equipment:

- Avoid the use of combinations of metals that lie far apart in the galvanic series.
- When small metal units are in direct contact with larger masses of metal, they should be more noble than the larger mass. For example, mechanical bolts of steel alloyed with copper, nickel, and chromium will not corrode when used in ductile-iron pipe joints.
- Provide the best available coatings and paints in enclosed, humid environments within the treatment plant and pumping stations, especially those where chlorine-bearing atmosphere occurs.
- Avoid extensive reliance on sacrificial coatings, such as galvanizing (zinc) on permanent structures.
- Recognize the passivating effect of structural constituents. For example, carbon in gray-iron and ductile-iron, concrete on steel, and noble metals as constituents of steel alloys will all increase corrosion resistance.
- Watch for sites of stress, fatigue, fretting, and crevice corrosion, and specify metals that are most resistant to these problems.

## TRENCH IMPROVEMENT

Generally, trench improvement of corrosive soils to reduce their corrosive tendencies is impractical. Extensive studies have been made of bedding and backfilling around underground pipe with sand, limestone, limestone screenings (fines), dolomite, sand plus 10 percent cement, and select soil. Although some reduction in corrosion incidence is realized with most of these treatments, it has been observed that, in many instances, the substitute fill material eventually takes on the characteristics of the surrounding soil. The long-term result can be inadequate protection.

## PROTECTIVE METHODS FOR SPECIFIC PIPE MATERIALS

Experience has shown that for any given pipe material, certain protective measures or combinations of protective measures are generally most effective and most economically feasible. This section briefly considers several of the pipe materials commonly used in water utility systems, with attention to the protective measures that have often been found appropriate.

## Steel Pipe

Coatings for corrosion control of steel pipe are extremely effective when properly used. They are considered to be the primary line of defense against corrosion of steel pipeline systems. AWWA has developed standards for widely used protective coatings that have provided years of effective corrosion control for buried steel pipelines. The coatings currently covered include coal tar enamel, shop-applied cement–mortar coating, cold-applied tapes, coal tar epoxy coatings, fusion-bonded and thermally activated coatings, extruded polyolefin coatings, and tape coating systems. A light-colored coating system is recommended for steel pipe exposed to the atmosphere, and recoating may be necessary at a time frequency dependent on the exposure condition.

The following corrosion control provisions are recommended for all buried steel pipeline:

- Apply a cement–mortar or other protective lining.
- Apply a cement–mortar or dielectric coating.
- Install and handle the pipe in accordance with project specifications and good construction and installation practices.
- Electrically bond the gasketed joints of installed pipe (welded joints are internally bonded) and provide test stations at appropriate intervals to permit monitoring.
- Fill the exterior joint recesses with cement mortar or other protective system compatible with the coating system used.
- Check for holidays and repair any accidental damage to the coating prior to backfilling.
- Fill the interior joint recesses with cement mortar or other protective system compatible with the lining system used.

Under certain environmental conditions, cathodic protection of steel pipe may be appropriate in addition to the coatings. For supplemental protection of cement–mortar-coated steel pipe in certain environmental conditions, refer to the discussion in the section on concrete cylinder pipe in this chapter.

## Copper Pipe

Copper exposed to aggressive conditions should be isolated from the environment with an inert moisture barrier, a wrapping of insulating tape, a coating of an asphaltum paint, or with another appropriate material. Cathodic protection may also be necessary if copper pipe is coated.

## Concrete Cylinder Pipe

Where the chloride content of the soil dictates the need for supplemental protection of concrete cylinder pipe (see chapter 3), one of the following should be provided:

- a moisture barrier to protect the pipe exterior and/or electrical continuity (bonded joints) and a system for monitoring corrosion activity;
- silica fume in an amount equal to 8–10 percent of the cement content added to the exterior mortar or concrete cover over the reinforcing steel.

If concrete cylinder pipe will be installed in granular soils with a pH of 5 or less, the total acidity should be determined. If total acidity is 25 meq/100 g of dry soil or greater, one of the following measures should be used:

- Backfill the pipe zone with consolidated clay.
- Backfill the pipe zone with consolidated limestone.

- Provide an acid-resistant membrane or barrier coating on the pipe exterior.
- Use silica fume in an amount equal to 8–10 percent of the cement weight in the exterior mortar or concrete over the reinforcing steel.

In any soil with a pH below 4, the pipe should be installed in an envelope of consolidated clay or with an acid-resistant membrane or barrier coating on the pipe exterior.

When a potential problem with aggressive carbon dioxide is indicated by a soil and groundwater analysis (see chapter 3), one of the following steps should be implemented:

- Encase the pipe in a clay backfill.
- Apply a membrane, a sealer, or a barrier coating to the pipe exterior.

For concrete cylinder pipe continuously submerged in seawater, Type II cement, which contains 8 percent or less tricalcium aluminate ($C_3A$), should be specified for sulfate resistance. In soils with more than 2,000 ppm water-soluble sulfate, one of these measures should be taken:

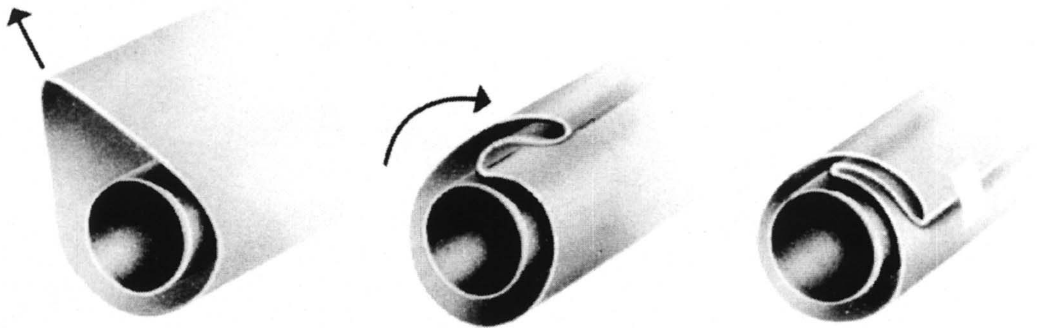
- The $C_3A$ content of the cement in the exterior concrete or mortar should not exceed 5 percent.
- Silica fume in an amount equal to 8–10 percent of the cement weight should be added to the external concrete or mortar covering the reinforcing.
- Apply a membrane or barrier coating to the pipe exterior.

When concrete cylinder pipe will be installed without earth cover, additional protective measures are desirable due to the long-term atmospheric exposure. The external surface of the pipe should be sealed with a coating material that is compatible with concrete or mortar substrates to prevent the admittance of moisture. A light color should be selected for the sealer to reflect sunlight and avoid large temperature differentials. Scheduled inspections and maintenance touch-up of the protective treatment are considered good practice.

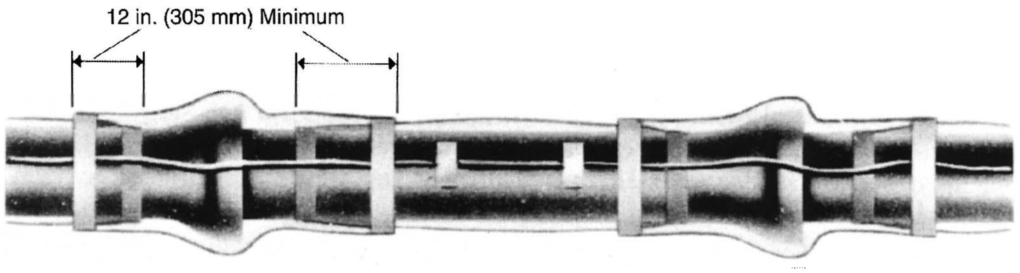
## Polyethylene Encasement of Ductile-Iron Pipe

Ductile-iron pipe is manufactured in 18- and 20-ft (5.5- and 6-m) lengths, and all modern joints use rubber gaskets. Because of this, a ductile-iron pipeline is a series of electrically segmented units. Experience has demonstrated that the joints retain resistance even after years of burial. Older gray-iron pipe was installed using other types of joints, such as caulked lead, sulfur compound, and cement, but the resistance of those joints is high enough that such pipelines are also considered electrically noncontinuous.

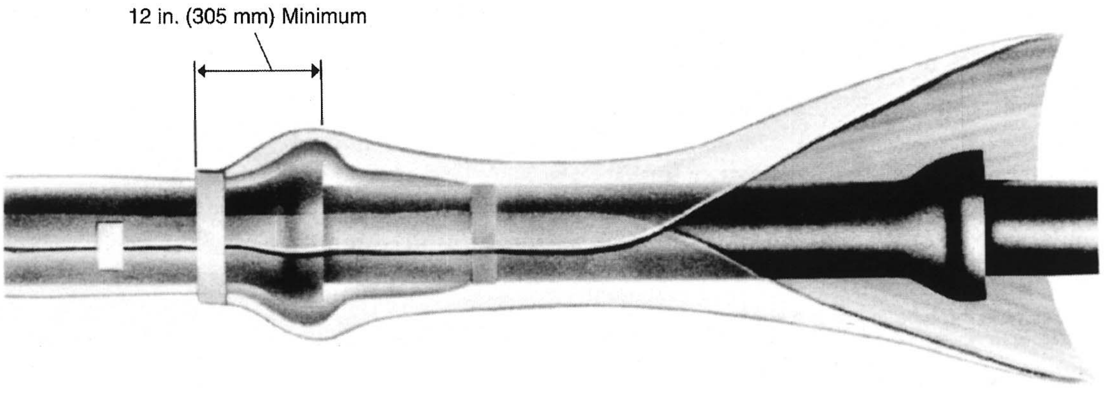
After years of study using adherent coating, trench improvement, and cathodic protection, the system of wrapping with 8-mil (0.008-in.) thick low-density, loose polyethylene encasement was researched and resulted in the development of ANSI/AWWA C105/A21.5, *Standard for Polyethylene Encasement for Ductile-Iron Pipe Systems*. During the 1993 revision to this standard, the section on materials was expanded to include 4-mil (0.004-in.) thick high-density, cross-laminated polyethylene. During the 1999 revision of the standard, the low-density polyethylene film was deleted and replaced with a much stronger and more damage-resistant linear low-density polyethylene film. In addition, impact- and tear-resistant requirements were added for both the new linear low-density and high-density cross-laminated films, along with marking requirements to facilitate traceability and to help ensure compliance with the standard. Research has shown that both 8-mil (0.008-in.) low-density and linear low-density or 4-mil (0.004-in.) high-density, cross-laminated polyethylene will provide corrosion protection to ductile-iron pipe in aggressive soils. There are three methods of installing the encasement, as shown in Figure 4-6. Method A, illustrated in Figure 4-6, is the most widely used. For installations of polyethylene encasement below the water table or in areas subject to



**Method A: Take up the slack in the tube to make a snug but not tight fit. Fold the excess back over the top of the pipe, securing the fold at quarter points along the length of the pipe.**



**Method B: Separate pieces of polyethylene tube for barrel of pipe and polyethylene tube or sheet for joints. The polyethylene over joints overlaps tube encasing barrel. (Method B is not recommended for bolted-type joints unless an additional layer of polyethylene is provided over the joint area, as in methods A and C.)**



**Method C: Pipe completely wrapped with flat polyethylene sheet.**

Figure 4-6 Three methods for polyethylene encasement of ductile-iron pipelines

tidal action, it is recommended that tube-form polyethylene be used with both ends sealed as thoroughly as possible with adhesive tape or plastic straps at the joint overlap. It is also recommended that circumferential wraps of tape or plastic straps be placed at 2-ft (0.6-m) intervals along the barrel of the pipe to help minimize the space between the pipe and the polyethylene. For more information on the installation or taping of ductile-iron pipe encased in polyethylene, refer to ANSI/AWWA C105/A21.5.

Polyethylene encasement is not a coating, although it offers some of the qualities of a coating, such as dielectric strength. It is mainly an environmental improvement.

First, it reduces the environment to a very thin space between the pipe and the loose wrap; second, it excludes direct exposure to corrosive soil. It does allow the entrance of groundwater into the annular space between the pipe and wrap; however, the corrosive characteristics of the water are soon depleted by the action of initial corrosion, usually oxidation. Extensive use of polyethylene encasement has demonstrated its effectiveness for gray- and ductile-iron pipe in the following respects:

- It provides a uniform environment for the pipe, which eliminates local galvanic corrosion cells.
- It offers good electrical shielding, which resists the assimilation of stray direct current.
- Because it is installed on the pipe at the time of pipeline construction, it is less likely to be damaged than factory-applied coatings.
- Pinholes and minor damage to the loose wrapping material do not diminish its protective ability.
- Rips, punctures, or other significant damage to the polyethylene film should be repaired.
- Initial cost of material and installation are very low, and there are no maintenance costs.

Research has shown that polyethylene encasement is a viable corrosion protection system for ductile- and gray-iron pipe in most environments. However, other options should be considered for “uniquely severe environments,” as defined in Appendix A of ANSI/AWWA C105/A21.5.

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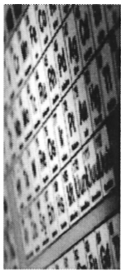

## *Chapter* 5

# Atmospheric Corrosion

## INTRODUCTION

Atmospheric corrosion, like corrosion underground or inside of water-containing pipes, is caused by electrochemical reactions. We define atmospheric corrosion as corrosion that occurs anywhere other than in direct contact with a continuous electrolyte such as soil or water. Examples of atmospheric corrosion include

- pipes on bridge crossings, either on top of or suspended beneath the bridge;
- pipes inside of treatment facilities that are exposed to the air;
- valves in manholes or pits where there is no water or soil surrounding the pipe;
- the exterior of storage tanks and standpipes; and
- exposed metal in treatment plants and wells.

As in underground or submerged corrosion, four things must be present for atmospheric corrosion to occur. First, there must be both an anode and a cathode present. Corrosion, or metal oxidation, occurs at the anode. Reduction occurs at the cathode. There must also be a metallic path for the electrons that are produced at the anode to reach the cathode for the reduction reaction(s). Lastly, there must be an electrolyte for ion movement. The major difference between underground or submerged corrosion and atmospheric corrosion is the thickness of the electrolyte. While the electrolyte in underground and submerged corrosion can be almost infinite, the amount of electrolyte in atmospheric corrosion is very thin. It can vary from obvious wet film from rain to invisible. Figure 5-1 illustrates these conditions.

The remainder of this chapter focuses on factors that influence atmospheric corrosion and how it is controlled.

## HOW METALS CORRODE IN THE ATMOSPHERE

### Effects of the Environment

There are seven environmental factors that influence atmospheric corrosion. These factors, moisture, air pollutants, temperature, the presence of poultices, solar radiation and wind, orientation, and sheltering, are discussed in the following paragraphs.

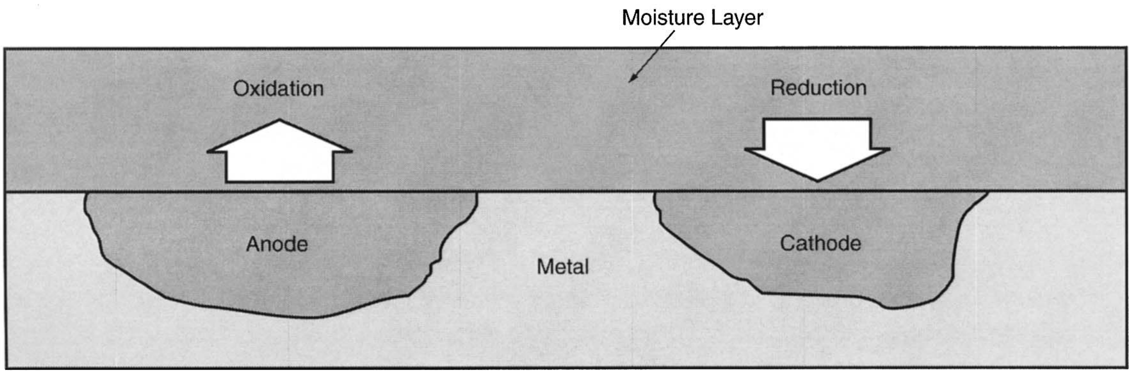

Figure 5-1 Atmospheric corrosion

Moisture is the most important factor. Moisture provides the electrolyte necessary for the anodic and cathodic reactions to occur. As previously stated, moisture is present only in a very small film usually from rainfall or condensation. There is a threshold relative humidity below which corrosion will not occur. The threshold relative humidity is dependent on the material and on the presence of air pollutants. For steel, the threshold relative humidity is 60 percent.

The concept of time-of-wetness is important in atmospheric corrosion. Time-of-wetness refers to the amount of time that moisture exists on the surface. Obviously, the longer moisture exists on the surface, the longer corrosion has to deteriorate the surface. A structure often has areas that have a moisture film longer than others (shaded or sheltered surfaces) and these tend to corrode more than surfaces that lose their moisture film early.

Air pollutants increase the corrosiveness of the moisture film. The most damaging air pollutants that accelerate corrosion are sulfur oxides (which form sulfuric acid that attacks passive layers and corrodes iron), chlorides (from deicing salts and marine environments), and particulates and aerosols (which retain moisture and other pollutants on the surface). Other corrosion-causing pollutants are nitrogen oxides, ammonia (causes stress corrosion of brass), hydrogen sulfide (attacks copper and steel), carbon dioxide, and ozone. Air pollutants, notably sulfur dioxide, decrease the threshold relative humidity, causing corrosion to occur at lower air moisture contents.

Temperature affects the relative humidity and dew point, the time of wetness, and the kinetics of the corrosion reaction. The dew point is the point where the combination of relative humidity and temperature causes moisture to condense on a surface.

A poultice is any material that traps and retains moisture and air pollutants. An accumulation of soil, dirt, organic matter, or other similar medium that can hold moisture and pollutants against the surface will increase the corrosion of that surface.

Solar radiation and wind affect the time of wetness. Wind affects the accumulation of particulates. Chlorides, moisture, or other contaminants blown by the wind can be deposited on surfaces, causing local corrosion in the direction of the prevailing wind. Solar radiation (ultraviolet light exposure) also affects the life of protective coatings on the surface.

The orientation of a surface affects how it will be affected by atmospheric corrosion (Figure 5-2). A surface that is shaded from sunlight will tend to stay moist longer than one that is heated by sunlight. The longer moisture stays on the surface, the more corrosion (remember time of wetness). Similarly a surface that is shielded from the wind will tend to stay moist longer and suffer more corrosion. Horizontal surfaces

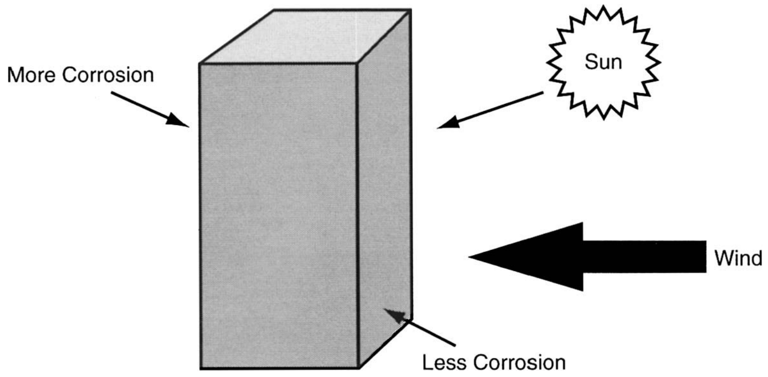

Figure 5-2 The effects of orientation on atmospheric corrosion

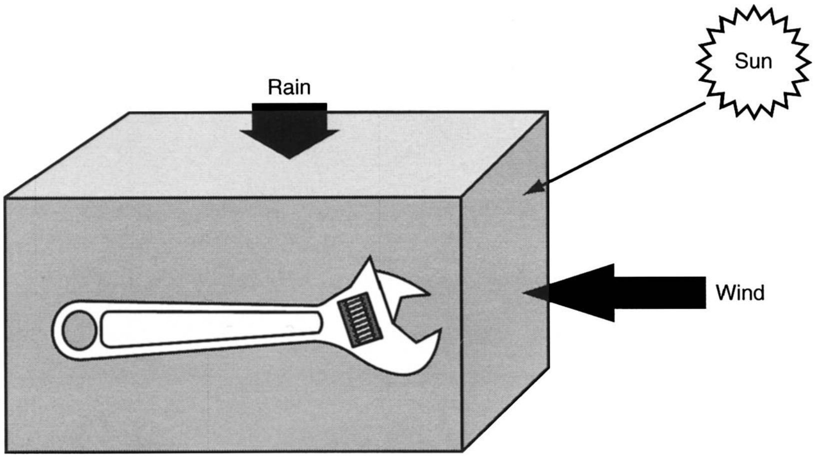

Figure 5-3 The effects of sheltering on atmospheric corrosion

facing up will be washed by rain and will not collect contaminants; however, if the surface is not drained and moisture collects, so can contaminants, leading to increased corrosion. Downward facing horizontal surfaces corrode more than their upward facing counterparts because they collect condensation.

Parts that are sheltered from the elements may be corroded less than those that are exposed (Figure 5-3). On the other hand, moisture can condense on sheltered objects and the sheltering will prevent drying. Moisture can diffuse through seals and condense inside an enclosure, resulting in a buildup of moisture. The temperature inside sheltered environments can rise higher than outside the enclosure, increasing corrosion rates.

The previous discussion listed many factors that affect atmospheric corrosion. In fact, any number of factors can be active on any structure, and they can be different in different areas of the structure. Changes in orientation, sheltering, and exposure to sunlight and winds will affect different parts of the structure differently. The total environment needs to be taken into account when designing corrosion control.

# TYPES OF CORROSION THAT CAN BE EXPECTED

Metals corrode in the atmosphere similarly to metals that are immersed. There are some characteristics that differ, however. The following discussion will explain.

## Types of Corrosion

**Uniform corrosion.** Uniform corrosion is the general wastage of metal where the entire surface seems to corrode at the same rate. Since atmospheric corrosion does not always occur at a constant rate (for reasons to be discussed), corrosion products sometimes form in a layered or flaking fashion. Large volumes of corrosion product can build up.

**Pitting corrosion.** Pitting occurs in a localized area. Pitting and uniform corrosion often occur together in atmospheric corrosion.

**Crevice corrosion.** The form of crevice corrosion that occurs most in atmospheric exposure occurs between two closely spaced objects, such as back-to-back angles on a pipe support bracket. The volume of corrosion products is considerably larger than the actual volume of metal corroded. The extra volume of the corrosion products exerts a tremendous force on the joint. Forces as high as 10,000 psi (68,950 kPa) can be exerted. One common effect of this force is the spalling of concrete on bridges contaminated with deicing salts. This force can actually deform the metal bounding the corrosion. This type of corrosion is often called pack rust, as shown in Figure 5-4.

**Bimetallic corrosion.** Bimetallic corrosion occurs when two or more metals that are widely separated on the galvanic series are joined together. The connection between them forms the electronic path and the thin film of moisture on the surface bridges the two metals forming the galvanic corrosion cell. Bimetallic corrosion as it occurs in the atmosphere is usually limited to the area in the vicinity of the junction between the two metals since the moisture film is very thin and current attenuation occurs within a short distance. Long-line galvanic corrosion cells, such as exist in pipelines, do not occur in atmospheric corrosion.

Area ratios between the anode and cathode will affect the amount of corrosion that occurs on the anodic metal. For example, a steel screw (anode) connected to a stainless steel sheet (cathode) will suffer more corrosion than if the sheet were steel and the screw stainless steel because the area of the steel sheet anode is relatively larger than the screw.

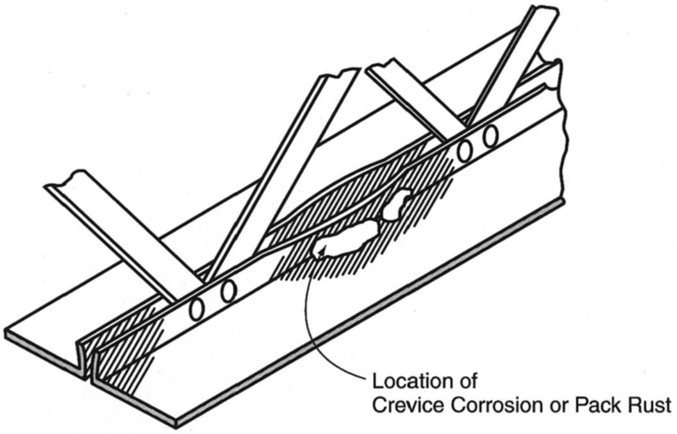

Figure 5-4 Crevice corrosion or pack rust

**Environmental cracking.** There are three types of environmental cracking—stress corrosion cracking, hydrogen embrittlement, and corrosion fatigue. Stress corrosion occurs when the metal has a tensile stress and there is a corrodant present. Examples are cracking of stainless steels and aluminum in chloride environments and brass in ammonia environments. Both types of stress corrosion cracking are possible in atmospheric exposure. Hydrogen embrittlement occurs when atomic hydrogen (hydrogen charging) enters a susceptible metal that is subjected to stress. Hydrogen charging can occur due to corrosion reactions or from excessive cathodic protection. For example, galvanized high-strength steel fasteners are subjected to stress corrosion cracking under highly corrosive conditions because the galvanic corrosion between the zinc and steel substrate generates hydrogen that is absorbed by the steel. Corrosion fatigue occurs when a susceptible material is subjected to a cyclic stress in the presence of a corrosive environment.

Figure 5-5 illustrates another type of stress-related corrosion caused by a galvanic corrosion cell between stressed and unstressed parts of a component. This type of corrosion is often found on fasteners where the heads and nuts are more stressed than the body of the fastener.

# METHODS OF CONTROL

Methods of corrosion control include materials, design, and coatings.

## Materials Selection

Common structural metals include carbon steel, weathering (high-strength low allow [HSLA]) steel, galvanized steel, stainless steel, aluminum, and copper. Each will corrode in the atmosphere, but at vastly different rates. Table 5-1 shows a comparison of typical corrosion rates for the common alloys.

This table basically shows that there are wide variations in the way different alloys perform in atmospheric corrosion. Carbon steel is the most common metal used in construction, but it corrodes at the highest rate. It is common, however, because it is inexpensive and can be protected readily, as will be discussed.

Weathering steel contains alloying elements that improve its atmospheric corrosion resistance. Weathering steel performs well in atmospheric exposure as long as

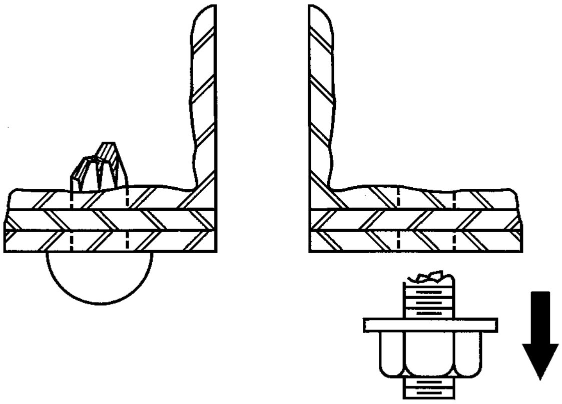

Figure 5-5 Stress-related galvanic corrosion of fasteners

Table 5-1 Comparison of uniform corrosion rates of different metals in the atmosphere

| | Rural | Urban | Industrial | Marine |
|---|---|---|---|---|
| Carbon steel | 4–65 | 23–71 | 26–175 | 26–104 |
| Weathering steel | 5–27 | | 4–68 | 7–85 |
| Stainless steel (300 series) | | 0.002–0.01 | 0–0.02 | <0.03–0.03 |
| Copper | 0.35–0.51 | | 1.27–3.05 | 0.15–1.52 |
| Galvanized steel | 0.2–3 | 2–16 | 2–16 | 0.5–0.6 |
| Aluminum* | 0.01 | 1 | 0.8–13 | 0.4–0.6 |

NOTE: Corrosion rates µm; µm = $10^{-6}$ m = 0.00003937 in.

* Source: ASTM STP 558, *Corrosion in Natural Environments*, 1973, ASTM, West Conshohocken, PA. ASM Handbook Volume 13: *Corrosion*. 1987. ASM International, Materials Park, Ohio.

the exposure conditions are not too severe (a marine environment is too severe as is exposure to deicing salts). Weathering steel must also be able to dry out once wetted, otherwise it does not develop its protective scale. Weathering steel should not be used where it cannot dry out, such as in enclosed areas or where tight-fitting crevices occur.

Galvanized steel is a good material for most applications. Remember that galvanized steel is really carbon steel with a thin layer of zinc that is about 0.0035 in. at a 2-oz/$\text{fl}^2$ coating. Once the zinc is depleted from corrosion, the steel will corrode at the same rate as carbon steel.

Stainless steel performs the best and copper and aluminum also perform well. Copper has long been used in architectural trim because of its excellent corrosion resistance. However, these materials may be expensive. That does not mean that they should not be used, perhaps not as the main structure, but as smaller, more difficult or more critical components where their superior corrosion resistance can be used effectively (keep bimetallic corrosion in mind).

## Design

Care in the design stage can often prevent corrosion problems from occurring. The goal in designing to control corrosion is to prevent, or lessen, one or more of the four elements needed for corrosion to take place (see Figure 5-1). The following are important points to consider when designing to prevent corrosion.

- Avoid dissimilar metals. Use only metals that are relatively close in the galvanic series of metals. This is not always possible. In fact, it is sometime necessary to use different metals to take advantage of the corrosion resistance of some metals where other methods of control are not practical. When it is necessary to combine different metals, use dielectric insulation or a sealant between them.
- Avoid crevices. Make back-to-back angles large enough so that the surfaces can be maintained (painted); otherwise, seal the joint with caulk or weld metal.
- Provide drainage. Design to avoid water entrapment if possible; otherwise, use weep holes where water cannot collect. Use large enough holes that the hole will not clog too quickly.
- Avoid debris entrapment.
- Design corrosion control to be independent. Do not rely on the corrosion control system of others for your structure. Provide protection sufficient to protect

your structure if it becomes exposed to the full environment. An example is a pipe crossing beneath a bridge with expansion joints—assume that the gutter system for the expansion joints will fail.

## Coatings

An effective coating system starts with a good set of specifications. Good specifications tell the contractor what is expected and provides a means of monitoring the coating process. Specifications consist of sections specific to the coating in addition to the routine contract provisions. These sections are type of structure to be coated, coating to be used, method of surface preparation, method of application, and inspection provisions.

There are two general types of coatings. Barrier coatings provide a border between the surface and the environment. Sacrificial coatings provide not only a barrier but also provide some cathodic protection at defects in the coating. Sacrificial coatings are metallic and are composed of active metals; in general, they are the same metals that are used as galvanic anodes in cathodic protection.

Examples of sacrificial coatings are electroplated zinc, hot-dipped zinc ("galvanized"), metallized zinc; aluminum-zinc (Galvalum); hot-dipped aluminum (Alumi-nize); electroplated cadmium (not used much anymore for environmental reasons); and zinc-rich paint (liquid applied).

Examples of barrier coatings are standard maintenance barrier coatings, including oil-based alkyd, silicone alkyd, and acrylic paints. Standard maintenance coatings are easy to apply, less sensitive to surface preparation when compared to high-performance coatings, and initially less costly than high-performance coatings. Generally, they have a shorter life than high-performance coatings in severe environments.

High-performance coatings include epoxy, polyurethane, vinyl, and zinc-rich coatings. These have a higher initial cost, are sensitive to surface preparation, but have a longer life than standard maintenance coatings if applied correctly.

To be successful, any coating needs to have the following properties: weatherability, corrosion protection, appearance retention, and maintainability.

A third class of coatings that is often considered when dealing with pipe crossings is standard underground pipe coatings. These include

- Coal-tar and asphalt. These are not recommended for atmospheric exposure, since coal tars and asphaltic coatings degrade rapidly when exposed to ultraviolet light.
- Petrolatum. This is an acceptable coating for atmospheric exposure when applied either with an external coating or is self-hardened for sunlight exposure.
- Extruded polyethylene. This is also a good coating, but must be formulated for ultraviolet light exposure.
- Fusion bonded epoxy. This coating will chalk at the rate of about ½ mil per year, so should be applied with a topcoat if appearance retention is important.
- Tape coatings. These must be formulated for ultraviolet light exposure.
- Polyurethane.

Coatings are applied as a system in one or more coats. Figure 5-6 illustrates this.

The primer forms the main bond with the substrate and is also the main corrosion-prevention element of the system. The topcoat forms the top layer, provides the weathering layer and aesthetic surface, and protects the primer from damage. An intermediate layer is frequently used to add thickness to the system, which increases the life of the coating system.

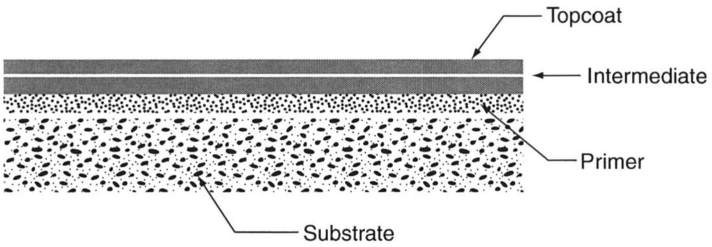

Figure 5-6 Application of coating system

Coating selection depends on

- Structure criticality: the effects of corrosion-related failure and aesthetics. It is important to tailor the coating to the environment.
- Exposure environment. Severe environments (e.g., marine, heavy industrial) require more durable coatings. In general, the high-performance coating systems perform longer in more corrosive environments.
- Life cycle cost. Consider the true cost of the coating system, not just the initial cost. A less expensive, low-durability coating will require several recoats within the life expectancy of the structure, while a more durable, more costly coating might require fewer recoats. The more costly (initially) coating could be less expensive in the long run.
- Ease of maintenance: ease of spot repair and recoatability of the paint. A high-performance coating might be justified if maintenance will not be performed.
- Environmental considerations. If previous coatings contain lead, overcoating may be feasible, or the old coating may have to be removed. If the old primer is intact, a coating suitable for overcoating might be economically justified. However, keep in mind that eventually the old coating will have to be removed. The costs of rigging and scaffolding are often the overriding cost factors. If this is the case, then removal of the old coating might be justified. If there are regulatory restrictions on volatile components, coatings that conform to the volatile organic compounds (VOC) regulations will be needed.

Surface preparation is perhaps the most important part of coating. The purpose of surface preparation is to remove surface contamination and create a profile ("tooth") for the primer to stick. In general, high-performance coatings require better surface preparation than ordinary maintenance coatings. The exceptions are the surface-tolerant epoxies and moisture-cured urethanes. As a general rule, the more severe the environment, the better the surface preparation should be. Surface preparation is normally specified by the National Association of Corrosion Engineers and Society for Protective Coatings (SSPC) standards. Typical standards are as follows (SP [surface preparation]):

| | | |
|---|---|---|
| SP2 | Hand Tool Cleaning | Normal maintenance coatings |
| SP3 | Power Tool Cleaning | Same + surface tolerant coatings |
| SP5 | White Metal Blast Cleaning | High-performance coatings |
| SP6 | Commercial Blast Cleaning | Some high-performance coatings |
| SP10 | Near-White Metal Blast Cleaning | High-performance coatings |
| SP11 | Power Tool Cleaning to Base Metal | High-performance coatings |
| SP12 | Surface Preparation and Cleaning of Metals by Waterjetting Prior to Recoating | High-performance coatings |

Coating application can be done by a number of methods, depending on the coating, the structure, and the conditions. The manufacturer should always be asked to provide recommendations when there is any doubt. Always apply the primer before the surface changes, usually within the same 8-hour shift. Otherwise, rust bloom can occur and require further surface cleaning. Application of the topcoat(s) should follow the manufacturer's recommendations regarding cure time and recoat intervals. Too fast a recoat could result in solvent entrapment, resulting in disbondment of the topcoat. Too long an interval between coats could result in disbondment, if the maximum recoat interval has been exceeded (important with epoxies and polyurethanes). All coating should be done with an eye on environmental conditions. The manufacturer's specifications regarding temperature and humidity must be followed. The temperature of the surface being coated should always be at least 5°F above the dew point, otherwise condensation on the metal could affect the coating cure and bond.

The work should always be inspected by a third-party inspection group, if possible. The purposes of inspections are to

- ensure that specifications are met;
- conduct tests for dew point, temperature, surface profile, surface preparation methods and procedures, surface profile and cleanliness, coating dry film thickness, recoating intervals, and containment and waste disposal compliance; and
- maintain a written record of events.

Inspection costs about 10 percent of the total painting cost; good inspection pays for itself in improved life of the coating system.

## COATING EVALUATION

The objectives behind evaluation of atmospheric corrosion is usually to test various products, mainly coatings, to determine how well they perform in the particular environment of your system. Coating an entire structure to see how the coating will perform can do this. However, it is more practical to test many coatings at one time, using test panels, say, 6 in. × 12 in., made of the same material as that on which the coating would be applied, usually steel. The coating is applied in the manner consistent with the manufacturer's specifications. The panel may be scribed or contain irregularities such as moisture traps or bolts. The test panel is installed in a representative location and examined periodically for appearance and ability to prevent corrosion. Long-term tests on a large number of coatings can be conducted in this manner. Using test panels to evaluate coatings is described in ASTM G50, *Practice for Conducting Atmospheric Corrosion Tests.* It is possible to run exposure tests at a commercial test facility located in a corrosive environment (e.g., marine or industrial facility).

Tests of various metals, such as aluminum, galvanized steel, and aluminized steel, can also be done using test panels. ASTM G1, *Preparing, Cleaning and Evaluating Corrosion Test Specimens*, discusses this type of test.

In any type of exposure test program, remember that many types of environments can exist on the same structure. It is important to test under the worst-case conditions as well as "normal" conditions.

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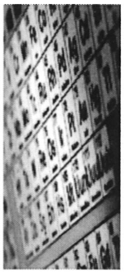

## Chapter 6

# Corrosion Control of Water Storage Tanks

Protecting the submerged, internal surfaces of water storage tanks from corrosion by cathodic protection is sound engineering practice supported by industry standards (ANSI/AWWA D104; NACE RP0388-88). The increased use of this technology has resulted from demonstrated economic benefits (Drisko 1972; Meyers and Obrecht 1975; Steel Fabricators Association 1977; Klimco 1995). Because many of the tanks contain potable water for consumption by the public, all system materials in contact with the water should be certified when possible in accordance with ANSI/NSF 61, *Drinking Water System Components—Health Effects*.

## CORROSION OF WATER TANKS

The corrosion of submerged metallic structures is caused by electrochemical activity. In freshwater tanks, corrosion activity usually results in a concentrated pitting attack that more quickly penetrates the steel plate than if the corrosion were more uniformly distributed on the metal surface. This attack is initiated by the development of anodic and cathodic areas on the submerged metal surfaces. Anodic areas will suffer metal loss, whereas cathodic areas will not.

### Mechanisms of Corrosion

There are a number of mechanisms that initiate corrosion of steel submerged in water tanks.

**Uniform corrosion.** Although steel visually appears to be homogeneous, close inspection shows that it is quite irregular, consisting of numerous grains of metal that are electrically different from each other. Thus, some will be anodes and others will be cathodes. The corrosion attack will usually appear as random, closely spaced pits.

**Stressed metal.** Usually steel that is under stress will be anodic to unstressed steel. In tanks, these stresses can be caused by welding or through bending or forming (without stress relieving), bolting, and riveting. Most often, the fastener will be anodic to the adjacent plate.

**Dissimilar metal corrosion.** The use of different metals in direct contact with each other will establish a corrosion cell in which the more noble metal will be cathodic and the more active metal will be anodic. Examples of such cells in tanks are copper or stainless steel heater coils in industrial fire protection tanks and weld seams where the metallurgy of the welding rod differs from the base plate metal.

**Crevice corrosion.** A corrosion cell develops at crevices where oxygen concentrations are lower than the adjacent area. The anodic area will be in the crevice, with the nearby surface areas cathodic. In water tanks, these develop most commonly between the head and plate of bolted or riveted plates and between the overlapping areas of unsealed plates.

**Differential in oxygen concentrations.** When steel is immersed in water and some of the steel surface is exposed to a relatively oxygen-enriched water compared with other steel surfaces, the area deprived of oxygen will be anodic in relation to surfaces exposed to highly oxygenated water. This phenomenon is often observed in bare or poorly coated tanks in which the lower submerged surfaces are heavily corroded (there are lower oxygen levels at greater depths), whereas the upper areas show little corrosion. Even more common is vertical striation corrosion. Deep, vertical gouges, sometimes several inches or even feet long, occur on the uncoated submerged surfaces of the tanks. This common corrosion phenomenon is caused by the development of an initial corrosion pit that generates soft, oozing corrosion products. Gravity causes these products to move down the side of the tank wall, shielding the lower surface from oxygen and rendering it anodic. The shielded surface begins to corrode, generating more corrosion products. The process continues over and over down the wall of the tank.

**Coating pinhole corrosion.** When the internal surfaces of tanks are coated with a dielectric material (e.g., epoxy), the corrosion activity will be concentrated at the holidays (holes) in the coating. The breaks in the coating can result from mechanical damage, improper surface preparation, or merely microscopic voids in the coating surfaces.

The corrosion currents will concentrate at the holidays and result in high corrosion current densities at these locations. Even though a good coating reduces the total metal loss, a complete penetration of the metal surface occurs more quickly than if the tank were not coated.

**The need for corrosion control.** Many other factors can influence the rate at which corrosion processes will proceed in water tanks. Among the most significant are electrolyte resistivity, water flow rates, the extent of anodic surface areas relative to cathodic areas, iron ion concentrations, temperature, and water level fluctuations.

Virtually all potable waters are corrosive with respect to steel. Almost all tank owners require that tanks be coated within a regular maintenance coating program or simply be entirely recoated every five years. Therefore, the question is not whether water tanks are subject to corrosion. The question is, what is the most effective and economical means of corrosion mitigation?

## CORROSION PREVENTION FOR WATER TANKS

The interior surfaces of water storage tanks should be protected from corrosion by coating and cathodic protection. The coating reduces the amount of bare metal in contact with the water, while the cathodic protection system provides corrosion protection at the unavoidable voids in the coating.

## Coatings and Cathodic Protection

A four-year study by the US Navy concluded (Drisko 1972):

> Cathodic protection has been shown to be an economical and effective method for protecting the immersed interiors of steel water tanks. Cathodic protection of a water tank can double or triple the time between recoatings. Thus, cathodic protection and protective coatings should be considered as components of a single corrosion control program for water storage tanks. Automatically controlled cathodic protection systems utilizing one reference half-cell should be installed in steel water storage tanks throughout the naval shore establishment.

Another report concluded (Meyers and Obrecht 1975):

> Supplemental cathodic protection should be used to prevent the corrosion that can occur at 'holidays' in organic coatings.

A brochure prepared by the Steel Plate Fabricators Association (1977) summarizes:

> The modern techniques of corrosion control using coatings and cathodic protection can reduce the initial cost and will extend the life of the steel storage tanks indefinitely.

The cost of installing cathodic protection is usually less than half the cost of repainting the submerged surface area of most tanks. Because cathodic protection can double or triple the time between recoatings, the economics of using cathodic protection for corrosion control on water tanks are apparent.

## Design of Cathodic Protection

A number of variables associated with each water tank must be considered when a cathodic protection system is designed. Among these are water chemistry, coating, tank design, and tank operations.

Variations in water chemistry that affect cathodic protection include the water source, total dissolved solids, total hardness, dissolved oxygen, total alkalinity, pH, temperature, and bacteria.

Variations in tank coatings include the generic type and condition of the coating. There are also a number of tank designs and shapes, including ground storage reservoirs, standpipes, and elevated water storage tanks. In addition, tanks are used as water storage facilities, pressure regulators, fire protection reservoirs, or any combination of these.

Because of these varying conditions, it would appear to be unreasonable to expect a limited number of cathodic protection designs to accommodate all. Yet, this is possible, because a number of conditions in water tanks and treatment equipment favor standardization.

First, the electrolyte (i.e., the water) in which the metal is submerged is relatively uniform. Second, although there are a number of structural shapes, they are all basically a combination of cylinders and gradual curves. These conditions contrast with those found in underground pipelines where there is considerable irregularity in electrolyte uniformity and piping configuration. Third, and most responsible for permitting standardized design, cathodic protection systems for water tanks are almost always of the rectifier type. Great flexibility can be built into a rectifier system to meet a variety of requirements without adding greatly to the cost. Magnesium and other types of galvanic anode materials are only used in specific circumstances because they are usually more costly than rectifier systems and are not as flexible.

When designing a cathodic protection system for a water storage tank, the designer must determine the total amount of current required for protection, the resistivity of the water, the anode materials, the anode geometry, and the service life.

The most important factor, however, is the type and condition of the coating. Although there are a number of coatings available for the interiors of water storage tanks, there appears to be an ever-increasing trend toward the use of epoxy coatings.

When a high-quality coating is applied and used with cathodic protection in accordance with AWWA standards and manufacturers' specifications, a useful life of 30 or more years can be expected. When it is realized that an uncoated water tank of 10-mil gal capacity can require as much as 150 A of current, whereas a similar well-coated tank might need as little as 5 to 10 A, the value of a quality coating system used in conjunction with cathodic protection is apparent.

A coating serves a different function on a cathodically protected structure. If coating is the only means of controlling corrosion, then blistering, peeling, or cracking of 1 to 2 percent of the coated surface causes failure of the paint system to control corrosion. In most cases, accelerated attack will occur.

In a cathodically protected tank, comparable coating deterioration is compensated for by a small increase in the cathodic protection system's electrical current output. The coating's major function with cathodic protection is to reduce the cost of power and the rate of anode consumption. Repainting the submerged portions of the structure can, therefore, be done less frequently.

## Cathodic Protection Anodes

In the past, if the anode material was not subject to winter icing damage, high-silicon cast-iron anodes were often used. These anodes had a minimum design life of 10 years and, therefore, eliminated the annual expenditure required to replace aluminum anodes.

If a water tank was subject to winter icing conditions, aluminum anodes were used. These expendable aluminum anodes were of extruded 2017-T4 alloy of at least 15 mm (½ in.) diameter and of sufficient size and length to provide for one full year of operation. These anodes must be replaced each spring.

An alternative to the roof-supported anode systems has been developed using a small-diameter, precious metal, wire-anode system. This system suspends the anode wire material in a circular loop configuration to conform to the geometry of the tank (Figures 6-1 and 6-2). The installation technique has several advantages. Primary among these is the fact that it provides the most even distribution of current for optimum performance, tailored to the size and shape of the particular tank.

This suspension technique is ideally suited where a long design life is desired in a tank subject to icing conditions. The flexible suspension system is designed so the anode material cannot come in contact with the tank ice during normal fluctuation in water level. As a result, the tank receives cathodic protection all year round and there is no need for yearly replacement of ice-damaged anodes.

The loop suspension system also eliminates the need for hand holes (plus covers and insulated support brackets) and the maintenance problems involved with these. There is no need to cut numerous holes in the top of the tank. Typically, this was done after the tank was coated, thereby creating the need for touch-up work. These hand holes were also subject to their own corrosion problems, as well as being a source for contamination if they were not tight-fitting. With the loop system, the limited number of small metal hangers required for the suspension material can be easily welded to the inside of the tank before the coating is applied.

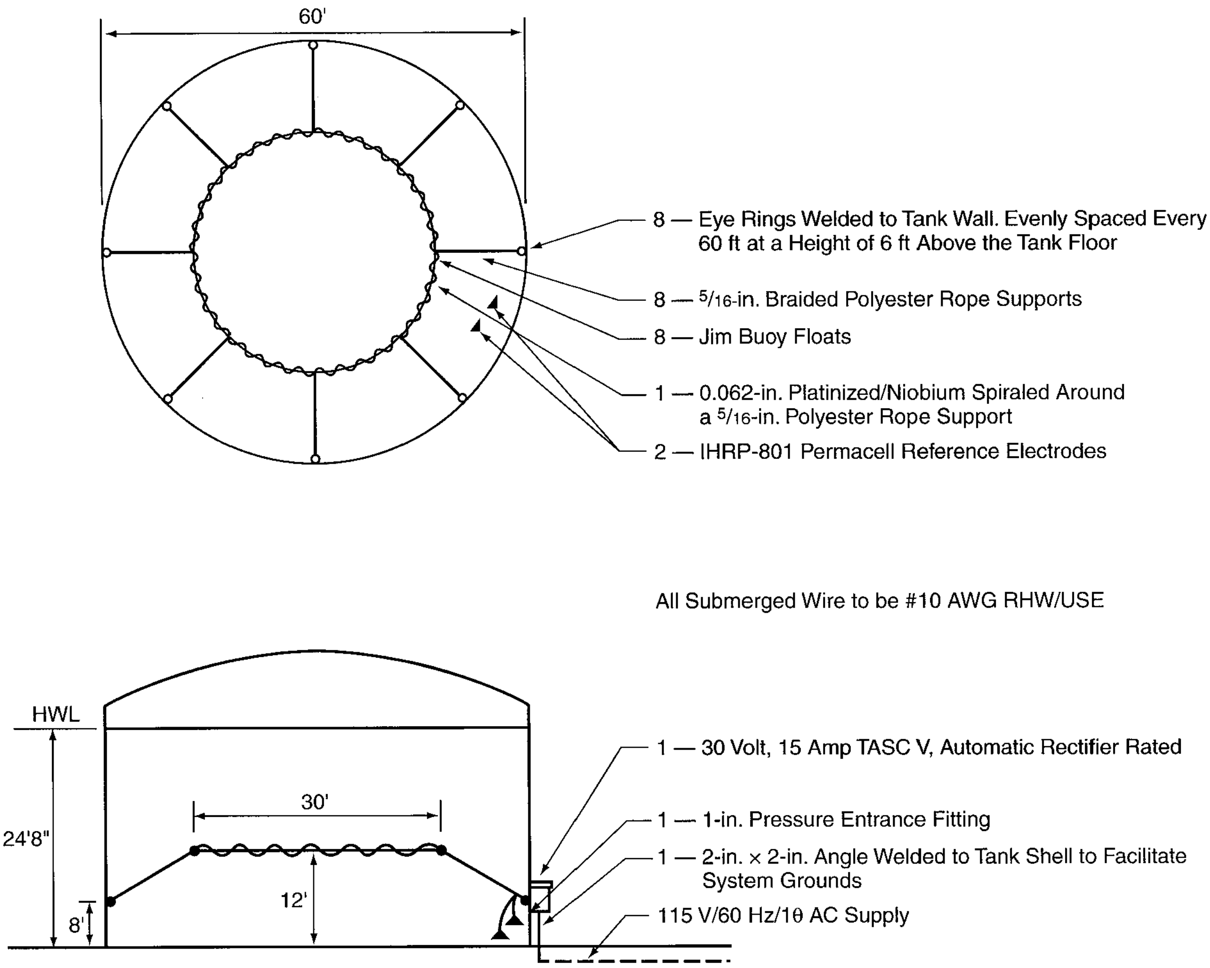

Figure 6-1 Typical cathodic protection system for ground storage reservoir

## Automatic Transformer-Rectifier

Several automatic control systems have been developed to compensate for changes in current requirements for cathodic protection. These changes result from fluctuating water levels, changes in water chemistry, and coating deterioration.

The US Navy report states (Drisko 1972):

> An automatically controlled cathodic protection system for steel water tank interiors is a reliable safeguard for ensuring that the immersed surfaces are receiving full protection from corrosion without excessive use of current or damage to the coating.

The study by Meyers and Obrecht (1975) concludes:

> Regardless of the coating efficiency, cathodic protection systems should be automatic potential controlled. This will ensure that any exposed steel immersed in the water is continuously being protected without excessive use of current or blistering of the coating.

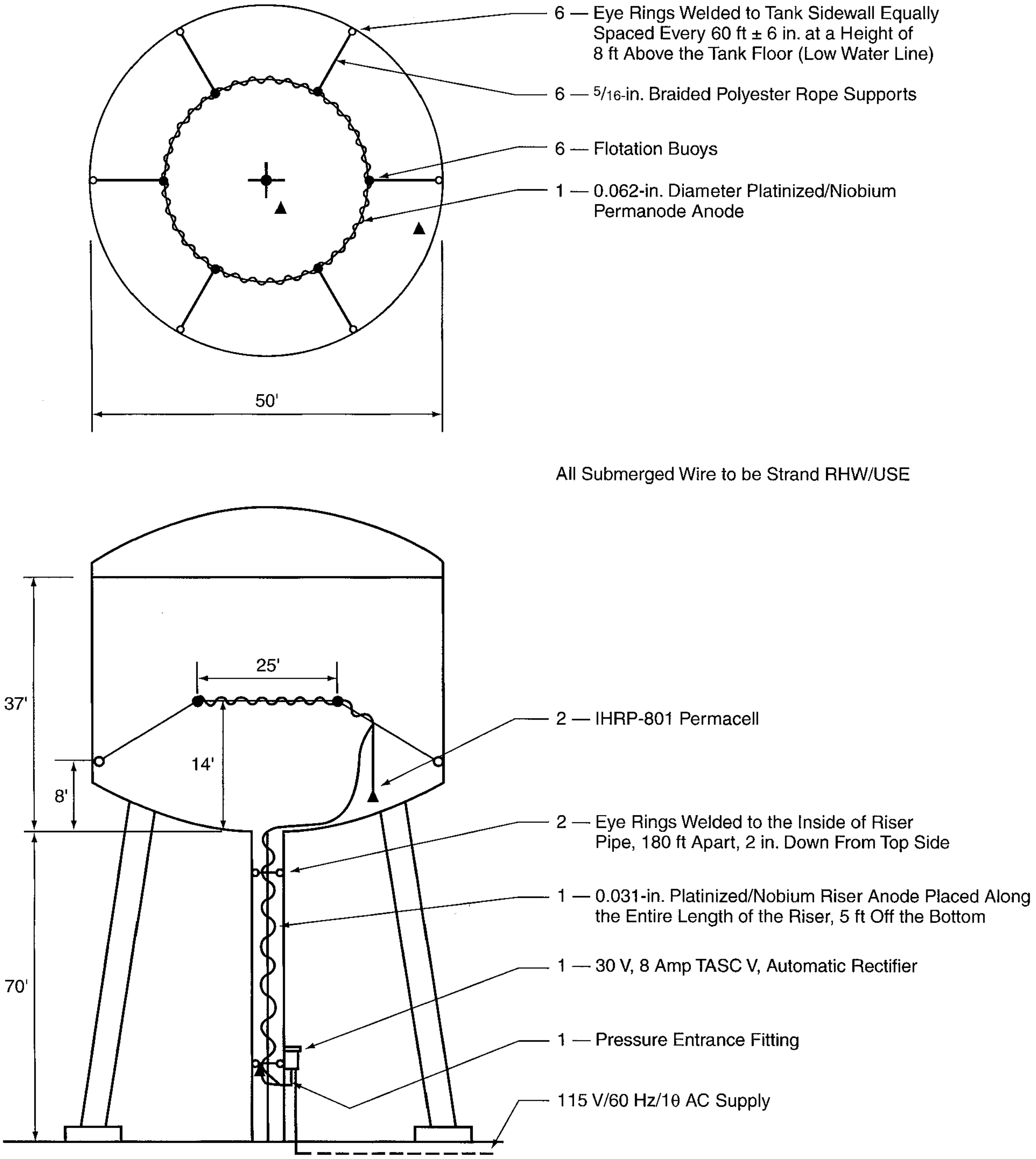

Figure 6-2 Typical cathodic protection system for elevated tank

Automatic voltage-control units incorporate a circuit that compares the difference in potential between the reference electrode and the tank against a preset internal voltage. When the structure-to-reference electrode varies from the optimum value, the circuit operates to increase or decrease the anode current so that the optimum voltage will be maintained.

Meyers and Obrecht (1975) state:

> The success of an automatic potential controlled cathodic protection system, however, depends upon how accurately the tank-to-water potential can be measured. IR drop error between the steel and a permanently installed copper–copper sulfate reference electrode must be eliminated if effective corrosion control is to be obtained.

The best method to eliminate the IR drop in the potential measurement is to reduce the current flowing from the anode to the tank wall to zero. This can be done by interrupting the current output from the rectifier unit. The reading taken immediately after the anode current is interrupted, called an instant-off reading, is maintained between –0.850 V and –1.050 V in a properly operating system.

This technique requires only one reference electrode, with no manual balancing or field compensations necessary. Through the use of solid-state components, the output of anode current for the rectifier is turned off for a fraction of a second, during which time the tank-to-electrolyte potential is measured by the reference electrode and electronically stored in a memory circuit. This memorized reading is then compared with a pre-set optimum potential and is used to control the output of current during the remaining time period, after which the system recycles. These systems are also equipped with a corrosion-potential–monitoring voltmeter, which is located in the circuit so that it measures and indicates the instant-off protective level maintained in the tanks.

The units in this type of system are equipped with an automatic gain control so that the system responds to a given deviation in potential and is automatically adjusted to match specific conditions. The advantages over manual control lie not only in automatically maintaining precise protective levels regardless of changes in water level, water chemistry, and coating deterioration, but also in affording a means of reading the level of protection. Continuous corrosion control can be assured by monitoring the tank's potential voltmeter.

### Design Life

Most of the components in cathodic protection systems for water storage tanks and water treatment equipment have a design life of 15 to 20 years. The electrical components and the rectifier units are capable of continuous operation over this length of time with little attention. The exception is the anode materials, which consume themselves at various rates. High-silicon cast-iron anodes can, through proper design, last 10 or more years in most applications, while the newer wire anode systems can be designed for a 20-year life.

### Maintenance

A complete inspection of the cathodic protection system should be performed annually. For manual systems, annual maintenance should include readjustment of the system to ensure proper operating levels for the coming year. For systems with aluminum anodes, this service should include the replacement of the anode material. For all manual and automatic systems, the annual inspection should include a potential profile of the submerged structure along with visual and electrical tests.

## CONCLUSION

Cathodic protection for the submerged surfaces of water storage tanks is an effective and economical method of corrosion control. Although bare steel tanks can be protected, both coating and cathodic protection are usually recommended for new installations.

Automatically controlled, solid-state rectifiers, which measure the maintained potential without IR drop error, are recommended. A flexible, long-lived anode system using wire anodes is recommended, although replaceable aluminum anodes can also be used. Vertically suspended, long-life, wire anodes can be used for tanks when icing conditions do not exist. All systems must be properly maintained to ensure continued effective operation and optimum corrosion control.

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# Glossary

**aggressive.** Corrosive.

**anode.** That part of a corrosion cell that is discharging current into the electrolyte and is corroding. Electrochemical oxidation occurs at this electrode.

**backflow.** The entrance of water or other liquid from any but the normal source of a potable water supply system.

**bacteriological corrosion.** Corrosion that results from the by-products of sulfate-reducing bacteria in media of very low or no oxygen content.

**bimetal couple.** A type of corrosion where two different metals or alloys are in contact with each other in a common media.

**cathode.** That part of a corrosion cell that is receiving current and is protected. Electrochemical reduction occurs at this electrode.

**cathodic protection.** Reduction of corrosion by making the metal a cathode. This is done by causing direct current to enter the structure's surface at all locations.

**coating.** An application of an adherent or mechanically bonded material between metallic structures and their environment (electrolyte).

**concentration cell.** A corrosion cell involving two identical electrode materials, with corrosion resulting from mechanical, physical, or chemical differences of the environments adjacent to the two electrodes.

**conductivity.** The ease with which an electrical circuit allows current to flow. Conductivity, measured in mhos or Siemens, is the reciprocal of resistivity.

**copper–copper sulfate electrode (reference electrode, or CSE).** A copper rod partially immersed in a copper sulfate solution inside a cylindrical tube with a porous bottom, creating the cathodic half of a galvanic cell. The copper sulfate provides excellent soil contact—much better than would the bare copper rod. A reference electrode made with this cell is used in making field measurements of pipe-to-soil potentials.

**corrosion (general).** Deterioration of a material by reaction with its environment.

**corrosion (metallic).** Deterioration of a metal by reaction with its environment. This is nature's way of returning refined metals to their natural state. Rust is iron oxide—iron ore also is iron oxide.

**corrosion cell.** The arrangement of an anode and a cathode in contact with a common electrolyte in such a manner that current discharges from the anode into the electrolyte. Corrosion cells are either galvanic, which generate electrical current, or electrolytic, which are driven by an outside electric current.

**corrosion control.** The reduction in the rate of deterioration and/or the total elimination of the environmental impact on water utility systems.

**CSE.** *See* copper–copper sulfate electrode.

**current.** The movement of electricity through a circuit, measured in amperes (A). Conventional electrical current flow is said to move through an external circuit from the positive terminal (cathode) to the negative terminal (anode) of a galvanic cell; electrons actually move in the opposite direction, from negative to positive. Electrical current is analogous to flow rate in a water pipe.

**current span.** The amount of current moving through a pipe, calculated using the measurement of the difference in voltage between two locations along the pipeline.

**dezincification.** Selective removal of zinc from an alloy, such as brass.

**electrode.** One of two pieces of metal that are immersed in an electrolyte to form a corrosion cell. The corroding electrode, from which electrical current enters the electrolyte, is called the anode. The protected electrode is called the cathode.

**electrolyte.** The ionically conductive media in which the anode and cathode of a corrosion cell are immersed.

**electrolytic corrosion cell.** A cell in which an external direct current generates the corrosion.

**electron ($e^-$).** A constituent of an atom with a negative charge. Electrons flow in the direction opposite to current flow.

**electronic path.** The movement of electrons through a complete electrical circuit.

**environment.** The surrounding materials and conditions that influence the water utility system.

**environmental alteration.** The selection of an electrolyte (backfill material) to eliminate or reduce the rate of corrosion. Also referred to as trench improvement.

**Faraday's law.** A law of electrochemistry that states that the amount of any substance dissolved or deposited in electrolysis is proportional to the total electric charge passed.

**fatigue corrosion.** *See* stress corrosion.

**fretting corrosion.** *See* stress corrosion.

**galvanic corrosion cell.** A cell that generates direct electrical current.

**galvanic series.** A list of metals and alloys arranged according to their relative corrosion potentials in a given electrolyte.

**ground-voltage gradients.** A record of the voltage differences between each two of a series of locations along the ground surface.

**holiday.** A void in a coating that will allow the passage of electrical current.

**hot spot.** An area of soil found by survey and analysis or experience to be more corrosive than surrounding soil.

**impingement corrosion.** Localized attack caused by turbulence, cavitation, or other erosion that breaks through corrosion scale.

**impressed-current system.** A cathodic protection system utilizing an outside source of power, converting it to direct current, and injecting it into the soil through an anode bed. Also called a rectifier-ground-bed system.

**ion.** One of the electrically charged particles produced by the disassociation (breakup) of a chemical compound.

**mitigate.** To moderate or make less severe.

**Ohm's law.** A fundamental law of electricity that states that the current $I$ flowing in a circuit is equal to the voltage $E$ divided by the resistance $R$. Thus, $I = E/R$, where $I$ is in amperes, $E$ in volts, and $R$ in ohms.

**oxidation-reduction potential (redox potential).** The electrical potential (in millivolts) between platinum and reference electrodes inserted in soil, measured with a pH meter. A low potential indicates low soil aeration.

**passivation.** A condition of metal or alloy, usually at its surface, causing it to behave in a more noble manner.

**pH.** The hydrogen ion activity of a media. Values range from 0 to 14. A pH of less than 7 is acidic, 7 is neutral, and greater than 7 is alkaline.

**pH meter.** An instrument used for the electronic determination of pH. pH can also be measured with colorimetric or other analytical chemical methods.

**pipe-to-soil potential.** The potential measured between an underground metal, such as pipe, and a copper–copper sulfate electrode. Any two connected metals develop an electrical potential (driving force in volts) when in contact with a common media, such as soil.

**pitting corrosion.** Highly localized corrosion that causes penetration into the metal at a few spots.

**polarization.** Retardation of the corrosion process by the buildup of protective layers on an electrode, usually the cathode or anode.

**polar solvent.** A solvent compound whose molecules are polarized. That is, the electrostatic charge on one side of the molecule is relatively positive and, consequently, relatively negative on the other, due to unequal sharing of electrons in the covalent bonding between the atoms. Polar solvents separate the structural units of the solvate by surrounding each ion with a cluster of solvent molecules held to the positive or negative ion by the oppositely charged end of the solvent molecule. Water ($H_2O$) and methanol ($CH_3OH$) are examples of highly polar solvents.

**polyethylene encasement.** An 8-mil (0.008-in.) polyethylene film placed around gray-iron or ductile-iron pipe to prevent corrosion.

**potential.** The force available to drive an electrical current through a circuit, measured in volts (V). It is analogous to pressure (head) in a water pipe.

**rectifier-ground-bed system.** *See* impressed-current system.

**resistance.** The tendency of an electrical circuit to retard the flow of current. It is measured in ohms (Ω), and is analogous to friction factor in a water pipe.

**resistivity.** A measure of the effective resistance of a media, such as soil, over a given distance. It is measured in ohm-centimeters (Ω-cm).

**resistivity meter.** An instrument that utilizes batteries and is used to measure the average resistance to current flow in a media.

**return current path.** The metallic connection between the anode and cathode of an electrochemical cell.

**return on investment.** A method to determine whether any proposed course of action will prove to be economical, as compared to other possible alternatives.

**sacrificial anode.** An anode of metal less noble than a metal structure to be cathodically protected. It is sacrificed by corrosion to create cathodic conditions at the protected structure.

**sacrificial-anode system.** A cathodic protection system in which the driving voltage for the protective current is generated by a galvanic corrosion cell, with the protected structure being the cathode.

**single probe.** A probe, usually 4 to 4½ ft (1.2 to 1.4 m) in length, used to measure resistivity soil around the tip or point of the probe.

**soil box.** A device used to determine resistivity of a confined volume of soil. The box is manufactured by several companies; however, one can be constructed conveniently. It measures 4 cm × 4 cm × 4 cm and two of the opposite sides are of stainless steel.

**soil corrosion.** Corrosion of underground materials resulting from soil conditions.

**soil resistivity.** An indication of difficulty with which a soil conducts electrical current. The average electrical resistance of a volume of soil.

**stray current.** Direct current traveling through the earth around an existing underground structure. If stray current enters and leaves that structure, corrosion will occur.

**stress corrosion.** Corrosion that acts on metal at points of tensile stress, working, or vibration wear.

**sulfides.** A chemical compound of sulfur with another element. A result of the life process of sulfate-reducing bacteria.

**voltage.** *See* potential.

# INDEX

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