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Chapter 2 Corrosion Theory and Corrosion Protection

2-1. Introduction

a. The annual cost of corrosion and corrosion protection in the United States is estimated by the National Association of Corrosion Engineers (NACE) to be in excess of 10 billion dollars. This figure is perhaps less intimidating considering that corrosion occurs, with varying degrees and types of degradation, whenever metallics are used.

b. Corrosion can be mitigated by five basic methods: coatings, cathodic protection, materials selection, chemical inhibitors, and environmental change. A basic understanding of corrosion will enable USACE personnel to comprehend how these methods help prevent corrosion, and it will establish an overall introduction to the purpose for the entire engineer manual on painting.

2-2. Causes of Corrosion

Corrosion is defined as the deterioration of a material, usually a metal, because of a reaction with its environment and which requires the presence of an anode, a cathode, an electrolyte, and an electrical circuit. To understand the application of protective coatings or cathodic protection in corrosion control, the basic concepts of corrosion of metals in the presence of moisture needs to be reviewed.

a. Corrosion occurs by an electrochemical process. The phenomenon is similar to that which takes place when a carbon-zinc "dry" cell generates a direct current. Basically, an anode (negative electrode), a cathode (positive electrode), an electrolyte (environment), and a circuit connecting the anode and the cathode are required for corrosion to occur (see Figure 2-1). Dissolution of metal occurs at the anode where the corrosion current enters the electrolyte and flows to the cathode. The general reaction (reactions, if an alloy is involved) that occurs at the anode is the dissolution of metal as ions:



where

M = metal involved
n = valence of the corroding metal species
e = electrons

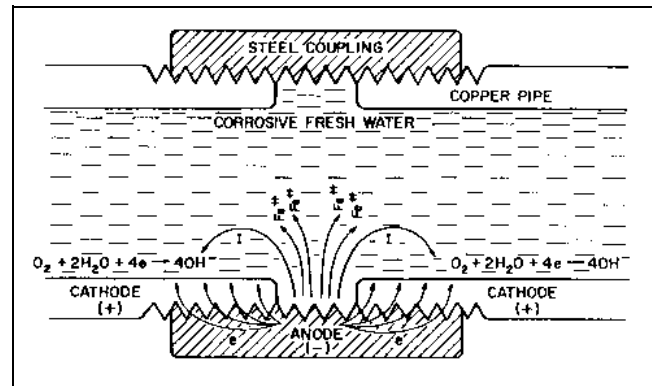
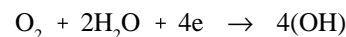
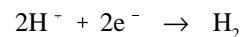


Figure 2-1. The basic corrosion cell consists of an anode, a cathode, an electrolyte, and a metallic path for electron flow. Note that the corrosion current (i) enters the electrolyte at the anode and flows to the cathode

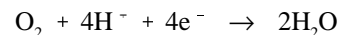
Examination of this basic reaction reveals that a loss of electrons, or oxidation, occurs at the anode. Electrons lost at the anode flow through the metallic circuit to the cathode and permit a cathodic reaction (or reactions) to occur. In alkaline and neutral aerated solutions, the predominant cathodic reaction is



The cathodic reaction that usually occurs in deaerated acids is



In aerated acids, the cathodic reaction could be

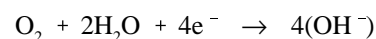


All of these reactions involve a gain of electrons and a reduction process.

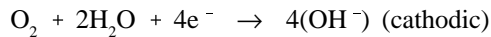
b. The number of electrons lost at the anode must equal the number of electrons gained at the cathode. For example, if iron (Fe) was exposed to an aerated, corrosive water, the anodic reaction would be



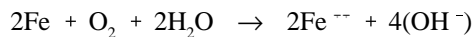
At the cathode, reduction of oxygen would occur



Because there can be no net gain or loss of electrons, two atoms of iron must dissolve to provide the four electrons required at the cathode. Thus, the anodic and cathodic reactions would be



These can be summed to give the overall oxidation-reduction reaction



c. After dissolution, ferrous ions (Fe^{++}) generally oxidize to ferric ions (Fe^{+++}); these will combine with hydroxide ions (OH^{-}) formed at the cathode to give a corrosion product called rust (FeOOH or $\text{Fe}_2\text{O}_3 \cdot x \text{H}_2\text{O}$). Similarly, zinc corroding in an aerated, corrosive water (i.e., $\text{Zn} \rightarrow \text{Zn}^{++} + 2\text{e}^{-}$) will form the corrosion product $\text{Zn}(\text{OH})_2$. The important issue to remember is that anodic dissolution of metal occurs electrochemically; the insoluble corrosion products are formed by a secondary chemical reaction.

2-3. Forms of Corrosion

Almost all corrosion problems and failures encountered in service can be associated with one or more of the eight basic forms of corrosion: general corrosion, galvanic corrosion, concentration-cell (crevice) corrosion, pitting corrosion, intergranular corrosion, stress corrosion cracking, dealloying, and erosion corrosion.

a. *General corrosion.* With general corrosion (sometimes called uniform corrosion), anodic dissolution is uniformly distributed over the entire metallic surface. The corrosion rate is nearly constant at all locations. Microscopic anodes and cathodes are continuously changing their electrochemical behavior from anode to cathode cells for a uniform attack. The general corrosion rates for metals in a wide variety of environments are known, and common practice is to select materials with rates that are acceptable for the application.

b. *Galvanic corrosion.*

(1) Galvanic (dissimilar metals) corrosion occurs when two electrochemically dissimilar metals are metallogically connected and exposed to a corrosive environment. The less noble metal (anode) suffers accelerated attack and the more noble metal (cathode) is cathodically protected by the galvanic current. The tendency of a metal to corrode in a galvanic cell is determined by its position in the "galvanic series" of metals and alloys as listed in Table 2-1.

Table 2-1
Galvanic Series in Seawater at 25 °C (77 °F)

Corroded end (anodic, or least noble)
Magnesium
Magnesium alloys
Zinc
Galvanized steel or galvanized wrought iron
Aluminum alloys - 5052, 3004, 3003, 1100, 6053, in this order
Low-carbon steel
Wrought iron
Cast iron
Ni-Resist (high-nickel cast iron)
Type 410 stainless steel (active)
50-50 lead-tin solder
Type 450 stainless steel (active)
Type 304 stainless steel (active)
Type 316 stainless steel (active)
Lead
Tin
Copper alloy C28000 (Muntz metal, 60% Cu)
Copper alloy C67500 (manganese bronze)
Copper alloys C46400, C46500, C46600
Alloy 200 (active)
Alloy 6700 (active)
Alloy B
Chlorimet 2
Copper alloy C27000 (yellow brass, 65% Cu)
Copper alloys C44300, C44400, C44500 (admiralty brass)
Copper alloys C60800, C61400 (aluminum bronze)
Copper alloy C23000 (red brass, 85% Cu)
Copper C11000 (ETP copper)
Copper alloys C65100, C65500 (silicon bronze)
Copper alloy C71500 (copper nickel, 30% Ni)
Copper alloy C92300, cast (leaded tin bronze G)
Copper alloy C92200, cast (leaded tin bronze M)
Alloy 200 (passive)
Alloy 600 (passive)
Alloy 400
Type 410 stainless steel (passive)
Type 304 stainless steel (passive)
Type 3316 stainless steel (passive)
Alloy 825
Alloy 62
Alloy C
Chlorimet 3
Silver
Titanium
Graphite
Gold
Platinum
Protected end (cathodic, or most noble)

(2) The metal order listed in Table 2-1 is only appropriate for seawater at 25 °C (77 °F). The order may vary with both temperature and composition of the electrolyte (water or soil). In fact, under some conditions, two metals may reverse their water respective order (potentials). For example, iron may become anodic with respect to zinc in fresh water at a temperature above 66 °C (150 °F).

(3) A common galvanic corrosion cell occurs when

copper lines are connected to galvanized steel water mains. In this example, the soil is the electrolyte, the copper line is the cathode, and the water main is the anode.

c. Concentration-cell corrosion. Concentration-cell corrosion occurs because of differences in the environment surrounding the metal. This form of corrosion is sometimes referred to as “crevice corrosion,” “gasket corrosion,” and “deposit corrosion” because it commonly occurs in localized areas where small volumes of stagnant solution exist. Normal mechanical construction can create crevices at sharp corners, spot welds, lap joints, fasteners, flanged fittings, couplings, threaded joints, and tube sheet supports. At least five types of concentration cells exist; the most common are the “oxygen” and “metal ion” cells. Areas on a surface in contact with an electrolyte having a high oxygen concentration generally will be cathodic relative to those areas where less oxygen is present (oxygen cell). Areas on a surface where the electrolyte contains an appreciable quantity of the metal’s ions will be cathodic compared to locations where the metal ion concentration is lower (metal ion cell).

d. Pitting corrosion. Pitting corrosion is a randomly occurring, highly localized form of attack on a metal surface, characterized by the fact that the depth of penetration is much greater than the diameter of the area affected. Pitting is one of the most destructive forms of corrosion, yet its mechanism is not completely understood. Steel and galvanized steel pipes and storage tanks are susceptible to pitting corrosion and tuberculation by many potable waters. Various grades of stainless steel are susceptible to pitting corrosion when exposed to saline environments.

e. Intergranular corrosion. Intergranular corrosion is a localized condition that occurs at, or in narrow zones immediately adjacent to, the grain boundaries of an alloy. Although a number of alloy systems are susceptible to intergranular corrosion, most problems encountered in service involve austenitic stainless steels (such as 304 and 316) and the 2000 and 7000 series aluminum alloys. Welding, stress relief annealing, improper heat treating, or overheating in service generally establish the microscopic, compositional inhomogeneities that make a material susceptible to intergranular corrosion.

f. Stress corrosion cracking. Stress corrosion cracking (environmentally induced-delayed failure) describes the phenomenon that can occur when many alloys are subjected to static, surface tensile stresses and are exposed to certain corrosive environments. Cracks are initiated and propagated by the combined effect of a surface tensile stress and the environment. When stress corrosion cracking occurs, the

tensile stress involved is often much less than the yield strength of the material; the environment is usually one in which the material exhibits good resistance to general corrosion.

g. Dealloying. Dealloying is a corrosion process in which one element is preferentially removed from an alloy. This occurs without appreciable change in the size or shape of the component; but the affected area becomes weak, brittle, and porous. The two most important examples of dealloying are the preferential removal of zinc from copper-zinc alloys (dezincification), and the preferential removal of iron from gray-cast iron (graphitic corrosion). Graphitic corrosion sometimes occurs on underground cast iron water mains and leads to splitting of the pipe when the water pressure is suddenly increased.

h. Erosion corrosion. Erosion corrosion refers to the repetitive formation (a corrosion process) and destruction (a mechanical process) of the metal’s protective surface film. This typically occurs in a moving liquid. Erosion may be impinging (in the case of a pipe ell) or sliding (pipe wall) when it occurs. An example is the erosion corrosion of copper water tubes in a hot, high velocity, soft water environment. Cavitation is a special form of erosion corrosion.

2-4. Corrosion Mitigation

Corrosion mitigation can be accomplished by design considerations, by employing corrosion-resistant materials of construction, by employing cathodic protection, by using protective coatings, or by using inhibitors.

a. Design considerations. The use of acceptable engineering practices to minimize corrosion is fundamental to corrosion control. This is accomplished by engineering design. One of the most important factors in designing for corrosion control is to avoid crevices where deposits of water-soluble compounds and moisture can accumulate and are not accessible for maintenance. Any region where two surfaces are loosely joined, or come into proximity, also qualifies as a crevice site. Joining geometries also present various crevice corrosion problems. Examples include: bolting, back-to-back angles, rough welds, weld spatter, sharp edges, corners, discontinuities, and intermittent welding.

(1) Crevice corrosion. Crevice corrosion relies on establishing a crevice geometry to allow water or other liquids or deposits to enter the crevice. One form of corrosion prevention is to eliminate crevice geometry by design. Joints and fastenings should be arranged to give clean, uninterrupted lines; therefore, welded joints are

preferable to bolted or riveted joints. Sound welds and complete weld penetration will help to avoid porosity and crevice development that often result from intermittent welding, rough welds, and weld spatter. Grinding sharp edges, corners, welds, and weld spatter will help prevent crevice corrosion, as well as paint striping procedures over similar surfaces. Striping is a procedure that entails brush or spray application of the primer or, in some instances, the entire coating system over potential corrosion sites. Striping is designed to give additional barrier protection from the exposure, and it is common when the service environment includes some degree of immersion or splash.

(2) Stainless steel coupled to carbon steel. The galvanic series listed in Table 2-1 illustrates some of the common metals in seawater. The further apart the metals are in the series, the more rapid the corrosion of the more anodic metal will be. That is, a metal tends to corrode when connected to a more cathodic metal. For example, carbon steel will corrode more rapidly when connected to stainless steel.

(3) Stainless steel—active and passive states.

(a) Several grades of stainless steel appear toward the anodic (upper) end of the galvanic series when they are in the “active” condition, and at the cathodic (lower) end when they are in the “passive” condition. The corrosion-resistant nature of stainless steel is related to its inherent ability to form a protective oxide film in the presence of oxygen or various oxidizing chemicals such as nitric or sulfuric acid. If the protective oxide film is destroyed, the stainless steel is subjected to rapid corrosion (the active condition) in the presence of oxygen-free acids such as hydrochloric acid. Therefore, the correct application of a specific grade of stainless steel should include a determination if the oxidation level of the environment will result in a passive or active state.

(b) Stainless steels, particularly the 300 series, are subject to a heat treating effect called “sensitization” during welding and stress relieving between 427 °C (800 °F) and 760 °C (1400 °F). During welding, these stainless steels may form chromium carbides (at temperatures of 427 °C (800 °F) to 760 °C (1400 °F)). Therefore, the chromium near the grain boundaries is tied up and no longer forms the protective oxide film (chromium oxide). Thus, the grain boundaries are susceptible to intergranular corrosion and the stainless steel is no longer in the passive state. Sensitized stainless steels can deteriorate in acidic soil or water. This type of corrosion can be prevented by a solution treatment and repassivation process after welding.

(4) Unfavorable area differences. The rate of corrosion resulting from galvanic action frequently will depend on the

relative exposed areas of the two metals in contact. For example, zinc will corrode when connected to iron. The zinc will “protect” the iron by making it the cathode of the galvanic cell. This is the principle behind a zinc-rich coating on steel. Small anode areas, in combination with large cathode areas, should be avoided whenever possible. A small piece of zinc will corrode rapidly when coupled to a large area of iron, yet the iron will receive little protection. Coating less noble metals and leaving the more noble metal uncoated is not recommended. A poor coating application can reduce the service life of the metal significantly because of local defects which will cause accelerated anodic corrosion resulting from a galvanic action. Examples of these coating defects are pinholes, scratches, skips, and physical damage.

(5) Isolation of dissimilar metals. Galvanic attack may be prevented by using an insulator to prevent contact (completion of electrical circuit) between dissimilar metals. The more noble metal can be insulated from the less noble metal through the use of plastic washers for fasteners. Ceramics or nonconductive insulating materials also may be used.

(6) Connection of old and new materials. Galvanic corrosion is not limited to cells in which totally dissimilar metals are in contact and exposed to an electrolyte. Differences in the composition or surface condition of “similar” metals frequently can result in galvanic corrosion cells. For example, clean steel is typically anodic to corroded steel. Therefore, it is common in pipeline operations to find new pipeline installed in a repaired section or branch line corroding more rapidly than the old line to which it is connected. The older pipe causes accelerated corrosion of the new piping because of galvanic action. Local galvanic anode installation or the application of an insulator may prevent this problem.

(7) Electrical grounding. Steel pipe in soil or water, electrically connected to rebar in concrete, is another corrosion-related problem associated with galvanic cells. Steel pipe always should be prevented from contacting the reinforcing steel in concrete because the reinforcing steel is passive and will cause accelerated corrosion of the steel piping.

(8) Galvanized piping in 60 °C (140 °F) to 77 °C (170 °F) water. At normal ambient temperatures, galvanized steel is anodic to unprotected steel. The sacrificial action of the zinc is caused by the relative potential difference of zinc and iron at normal temperatures. However, in hot water applications, the potential of zinc decreases (becomes more cathodic) with an increase in temperature and actually may have the anodes and cathodes reversed. The steel would become anodic to the zinc.

Therefore, galvanized piping should not be used when water immersion temperatures are in the 60 °C (140 °F) to 77 °C (170 °F) range because the steel may become sacrificial to the zinc.

b. Cathodic protection. Cathodic protection is an electrical method of mitigating corrosion on metallic structures that are exposed to electrolytes such as soils and waters. Corrosion control is achieved by forcing a defined quantity of direct current to flow from auxiliary anodes, through the electrolyte, and onto the metal structure to be protected. Theoretically, corrosion of the structure is completely eliminated when the open-circuit potentials of the cathodic sites are polarized to the open-circuit potentials of the anodic sites. The entire protected structure becomes cathodic relative to the auxiliary anodes. Therefore, corrosion of the metal structure will cease when the applied cathodic current equals the corrosion current. There are two basic methods of corrosion control by cathodic protection. One involves the use of current that is produced when two electrochemically dissimilar metals or alloys (Table 2-1) are metallurgically connected and exposed to the electrolyte. This is commonly referred to as a sacrificial or galvanic cathodic protection system. The other method of cathodic protection involves the use of a direct current power source and auxiliary anodes, which is commonly referred to as an impressed current cathodic protection system.

(1) Sacrificial (galvanic) systems. Sacrificial-anode-type cathodic protection systems provide cathodic current by galvanic corrosion. The current is generated by metallurgically connecting the structure to be protected to a metal/alloy that is electrochemically more active than the material to be protected. Both the structure and the anode must be in contact with the electrolyte. Current discharges from the expendable anode through the electrolyte and onto the structure to be protected. The anode corrodes in the process of providing protection to the structure. The basic components of a single, sacrificial-anode-type cathodic protection installation are the structure to be protected, the anode, and the means of connecting the structure to the anode. This is shown in Figure 2-2.

(a) The cathodic current generated by the sacrificial anode depends on the inherent potential between the anode and the structure to be protected. Theoretically, any metal or alloy more electrochemically active than another would be capable of cathodically protecting the more noble material. In practice, only Type 2 zinc (99.9 percent Zn conforming to ASTM B418) and alloys of magnesium are used for the protection of steel in soils. Although zinc has a higher current output efficiency, most sacrificial anodes installed for the protection of underground steel structures are fabricated from magnesium alloys because magnesium

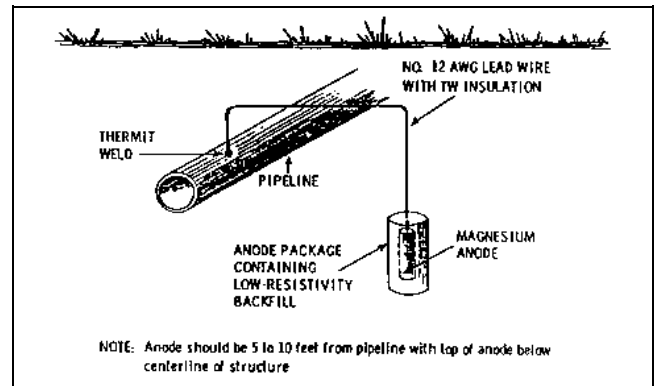


Figure 2-2. Schematic view showing sacrificial-anode-type cathodic protection installation for an underground steel pipeline

alloys provide a higher driving potential.

(b) Sacrificial-anode-type cathodic protection systems have a number of advantages:

- No external power is required
- No regulation is required
- Easy to install
- Minimum of cathodic interference problems
- Anodes can be readily added
- Minimum of maintenance required
- Uniform distribution of current
- Minimum right-of-way/easement costs
- Efficient use of protective current
- Installation can be inexpensive if installed at time of construction

(c) Sacrificial-anode-type systems also have disadvantages that limit their application:

- Limited driving potential
- Lower/limited current output
- Poorly coated structures may require many anodes
- Can be ineffective in high-resistivity environments
- Installation can be expensive if installed after construction

(2) Impressed current systems. Impressed-current-type cathodic protection systems provide cathodic current from an external power source. A direct current (DC) power source forces current to discharge from expendable anodes through the electrolyte and onto the structure to be protected. Although the current is not generated by the corrosion of a sacrificial metal/alloy, the energized materials used for the auxiliary anodes do corrode.

(a) The basic components of an impressed-current-type

cathodic protection system are the structure to be protected, a DC power source, a group of auxiliary anodes (ground bed or anode bed), and insulated lead wires connecting the structure to be protected to the negative terminal of the power source and the ground bed to the positive terminal of the power source. This is shown in Figure 2-3.

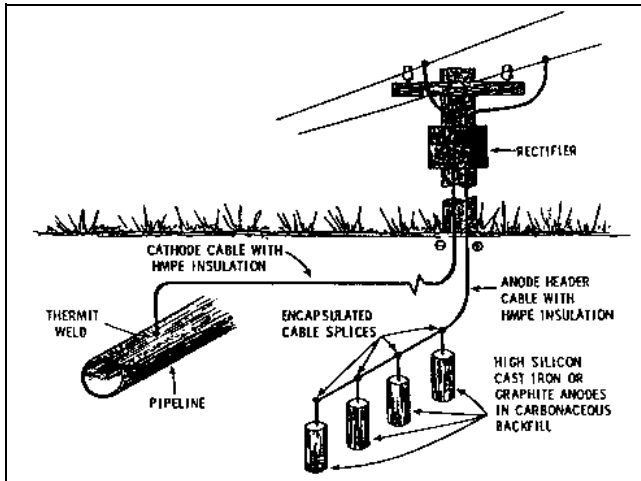


Figure 2-3. Schematic view showing impressed-current-type cathodic protection installation for an underground steel pipeline

(b) The DC power source is usually a rectifier, although current also can be obtained using engine-driven generators, batteries, solar cells, fuel cells, wind-powered generators, and thermoelectric generators. High-silicon chromium-bearing cast iron anodes and ceramic-coated anodes are commonly used materials for auxiliary anodes when impressed-current-type cathodic protection systems are used to mitigate corrosion on underground steel structures.

(c) Impressed-current-type cathodic protection systems have a number of advantages:

- Can be designed for a wide range of voltage and current
- High ampere-year output is available from single ground bed
- Large areas can be protected by single installation
- Variable voltage and current output
- Applicable in high-resistivity environments
- Effective in protecting uncoated and poorly coated structures

(d) Impressed-current-type systems also have disadvantages which limit their application:

- Can cause cathodic interference problems
- Are subject to power failure and vandalism
- Have right-of-way restrictions

- Require periodic inspection and maintenance
- Require external power, resulting in monthly power costs
- Overprotection can cause coating damage

(3) Systematic cathodic protection design procedure. The systematic cathodic protection design procedure provides the corrosion engineer an opportunity to evaluate the technical and economical benefits that result when several cathodic protection system designs are considered for a given project. The engineer is provided an opportunity to select the most advantageous system. Basically, the systematic cathodic protection design procedure is an optimization of the various existing methods. The procedure simultaneously considers both types of cathodic protection systems; it is applicable to both proposed and existing underground structures. Most important, the procedure provides flexibility in evaluating the alternatives, which are available in selecting the optimum cathodic protection system for the structure involved.

(a) During the predesign phase, basic information is obtained regarding the structure and its external environment. This information is collected by conducting and evaluating the results of selected field tests and considering the corrosion-control experience of other operations in the general area. The objective of the predesign phase is to determine the viability of cathodic protection as an effective means of corrosion control.

(b) The design phase sizes the cathodic protection system components. Initial iterations in the design phase, however, should be considered tentative. Once the tentative system components are selected, technical and economical life cycle costs must be calculated. Comparison of the various alternatives then can be made by evaluating each system's technical/economical benefits. Plans and specifications can be developed after design analysis; the system then can be installed. Following installation, the design procedure requires that the corrosion engineer conduct further field surveys to ensure that the protection criterion selected from NACE RP-01-69 is satisfied. The systematic design procedure also requires that, with an impressed-current-type cathodic protection system, additional field tests be conducted to ensure that no stray current corrosion problems exist. The procedure also requires that the corrosion engineer outline a cathodic protection system re-occurring maintenance program. The following publications should be referenced when designing either a sacrificial or impressed-current cathodic protection system: ETL 1110-9-10, ETL 1110-3-440, TM 5-811-7, and CWGS 16643.

(4) Monitoring effectiveness of cathodic protection systems. After a cathodic protection system is installed, the

system needs to be monitored. The system should be evaluated periodically to ensure that it is providing corrosion protection to the metallic structure. Criteria have been developed to determine if adequate corrosion protection is being achieved on the structure in question. For example, some of the indications of a cathodic protection problem include changes in operating conditions of the rectifier output and any noted corrosion increase of the structures.

(5) Criteria for cathodic protection. Structure-to-electrolyte potential measurements are analyzed to determine whether or not a structure is cathodically protected; these measurements are made by the use of cathodic protection criteria. Unfortunately, no one simple criterion has been accepted by all cathodic protection engineers that can be practicably measured in the field under all circumstances. Guidelines for selecting the proper criterion under various circumstances will be provided below. Guidance concerning the criteria of cathodic protection for external corrosion control on underground structures is found in two recommended practices (RP's) published by NACE. These are RP-01-69 and RP-02-85. A summary of the criteria for steel and cast iron structures follows.

(a) One criterion is a negative (cathodic) potential of at least 850 millivolts (mV) with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.

(b) A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode is another criterion. Polarized potential is defined as the potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

(c) Another criterion is defined as a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formulation or decay of polarization can be measured to satisfy this criterion. The -0.85 volt (V) potential criterion states that voltage drops other than those across the structure to electrolyte boundary must be considered when interpreting the measurements. Two criteria, "polarization" and "polarized potential," need to be considered. This is of utmost concern when evaluating potential measurements because only polarization provides cathodic protection. No protection is provided by the voltage drops other than those across the structure-to-electrolyte (i.e., structure-to-soil) boundary.

(6) CP diagnostic software. USACERL (U.S. Army Construction Engineering Research Laboratories) has developed a software package called CP Diagnostic that is helpful in evaluating the performance of cathodic protection systems and storing the data necessary to document the performance. The program stores background data about the cathodic protection system and protected structures, as well as all field data collected (including structure-to-soil potentials, anode-to-structure currents, isolation joint test results, and rectifier readings). The program automatically evaluates the structure-to-soil potentials against the criteria of cathodic protection and lists locations where protection is not being achieved. In addition, an expert system module is being developed to assist the field inspector in the troubleshooting of problems by leading the inspector through a series of questions. A diagnosis of the problem is then provided, and a remedy is suggested.

(7) Dielectric isolation. It may be desirable to electrically isolate a cathodically protected structure from all other metallic structures, such as connecting lines, pump stations, terminals, etc. If the installation is not isolated, these connections also will be cathodically protected, and current requirements frequently will be excessive. Electrical insulation of pipelines and other structures is accomplished by dielectric isolation. Small lines may be insulated by insulating couplings or unions. If feasible, insulated flanges should be assembled and electrically tested with an ohmmeter before being connected into a line.

c. Inhibitors. Any substance, when added in small quantities to a corrosive environment containing carbon steel or an alloy that will decrease the corrosion rate is called an inhibitor. Inhibitors function in various ways and are beyond the scope of this manual. Additions of soluble hydroxides, chromates, phosphates, silicates, and carbonates are used to decrease the corrosion rate of carbon steel and alloys in various corrosive environments. The concentration of a given inhibitor needed to protect a metal will depend on a number of factors such as composition of the environment, temperature, velocity of the liquid, the presence or absence in the metal of internal or external stresses, composition of the metal, and the presence of any other metal contact. The type and quantity of inhibitors required for a given metal may be determined by experiments. These experiments should include measurements on the location and degree of corrosive attack as a function of inhibitor type and concentration. Corrosive attacks may occur even if experimentation shows that adequate levels and the correct type of inhibitor are used. Small anode areas and increased attack may develop under loose scale, under deposits of foreign matter, in crevices, and in similar locations relatively inaccessible to the inhibitor.

d. Protective coatings. Coatings and linings play a significant role in corrosion prevention and are used extensively for this purpose. Coatings also can perform other valuable functions such as: provide easier cleanability, decontamination or graffiti removal, add color or a pleasing aesthetic appearance, increase light reflectance for a better working environment or for safety purposes, and provide a color marking or safety warning. There are many different types of coatings. Organic coatings are most commonly applied by brush, roller, or airless or conventionally atomized air-spray equipment. These coatings consist of an organic binder or film former with inhibitive, barrier, and sacrificial pigments for corrosion protection. Because of

the concerns regarding worker and environmental protection, many coating formulations are changing to the use of nontoxic, nonhazardous pigments and/or solvents, using water-based or high-solids binders. Metallic coatings such as thermal sprayed zinc, aluminum or aluminum-zinc alloys, stainless steel, and chromium can be used to protect against corrosion or provide increased wear or abrasion resistance. Zinc-rich coatings are widely used to provide galvanic corrosion protection to steel. Galvanizing (either strip or hot-dip) is another way of applying zinc to a steel surface for corrosion protection. Protective coating types are discussed in detail in Chapter 4.