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Cathodic Protection Application and Maintenance Guide

Volume 1: Buried Piping

2013 TECHNICAL REPORT

Cathodic Protection Application and Maintenance Guide

Volume 1: Buried Piping

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Volume 2 entitled *Cathodic Protection Application and Maintenance Guide - Volume 2: Plant Structures and Equipment* is also available. The companion guide covers cathodic protection application for other structures including condensers and heat exchangers, atmospherically exposed reinforced concrete structures, intake structures, steel pilings in soil, underground storage tanks, aboveground storage tanks, and meteorological tower guy anchors.

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PRODUCT DESCRIPTION

Many nuclear power plants are entering into life extension or are applying for license renewal; therefore, it is important for engineers and maintenance staff to focus time and effort on corrosion control systems that are designed to prolong the service life of buried piping to ensure reliable operation of the plant equipment. Cathodic protection (CP) is essential for maintaining any metallic structure in a corrosive environment at the lowest life cycle cost. By implementing an effective CP program, the premature failure of plant piping and tanks, causing foreign substance spills or—in the case of nuclear power plants—radioactive leaks, is greatly reduced.

This report is provided in two volumes: Volume 1 is for buried piping and Volume 2 is for plant structures and other equipment.

Background

Recent operating experience from nuclear power plants indicates that degradation of buried piping, tanks, and structures is becoming a maintenance issue. The vast majority of these plants, and particularly those in the United States, are now 30–40 years old. The design life of a typical impressed current CP system for buried piping is approximately 20–25 years. Many of the older CP systems have exceeded their original design life and now require upgrade, repair, and/or replacement. Some of these systems may not be providing adequate levels of CP to control corrosion of the buried piping, and corrosion-related failures may increase unless appropriate measures are taken. The design and installation of new CP systems may also be required at plants where new systems have been installed, at plants where degradation has occurred, or at plants where CP was not initially used.

Objective

To provide an application and maintenance guide that is specific to CP of buried piping at nuclear power plants. Both impressed current and galvanic anode systems are discussed.

Approach

Buried pipes in nuclear power plants provide a variety of services including water, fire protection, gases, fuel oil, and lube oil. Some of the pipes may also contain radioactive fluids. Buried piping may include ASME Class 2 or 3 safety-related systems that are important for plant shutdown. They may be constructed of several different materials including carbon steel, aluminum, aluminum-bronze, stainless steel, galvanized steel, ductile iron, cast iron, corrugated metal, copper alloys, titanium, concrete, asbestos, polyvinyl chloride (PVC), fiber reinforced pipe, and polyethylene. Buried pipes may be bare or have a variety of internal and external coatings and may encompass a wide range of sizes, ranging from over 10 ft (3 m) in diameter to small bore (that is, 2 in. [5 cm] or smaller). Depending on their location and function, buried pipes can vary in depth from several feet to 30 ft (9.1 m) or more below the finished grade. Finally, buried pipes at nuclear plants may have effective CP, marginal protection, or no CP at all.

To provide effective CP, the design engineer needs to take into account the current requirements, the location of electrical grounding, abandoned pipes, the coating condition, the electrical continuity of the systems to be protected, and locations of other buried structures that are in the vicinity of the anode groundbeds. Additional parameters needed for design include knowledge of the soil corrosivity, depth to bedrock, depth of the water table, structure and ground connections, equipment location, ac power availability, routing of direct buried cable, availability of duct work, and the number and location of test stations so that representative monitoring of the CP system performance can be provided. If prestressed concrete cylinder pipe is used, the CP design needs to take into account the type of prestressing wire since Class IV prestressing is susceptible to overprotection and hydrogen embrittlement. To help facilitate overall planning, the design and installation of the CP system should be coordinated with site operations at the plant, security, civil engineering, and electrical engineering, while taking into account the schedule for plant outages and plans for future expansion.

Results

Although this guide covers the application of CP, it also focuses on proper equipment selection, system monitoring, and maintenance of associated equipment. In order to plan and implement the appropriate maintenance methods to ensure adequate CP system performance, the materials; type of system (impressed current or galvanic); the considerations that went into making equipment selections; and the pre-testing, post-testing, and in-service testing methods should be understood, documented, and properly applied.

Application, Value, and Use

This guide provides power plant staff with information for establishing an effective application and maintenance program for CP systems and components. The target audience includes plant engineers, operators, maintenance personnel, and technicians. This guide provides an introduction to corrosion of buried piping, guidelines regarding equipment selection, CP system design and installation, periodic testing, troubleshooting, and recommendations for monitoring and maintenance. The guide outlines the most common failure modes, describes appropriate predictive and preventive maintenance techniques, and provides information on the methods available to optimize service life and minimize maintenance costs through effective preventive maintenance and condition monitoring.

Keywords

Buried piping
Cathodic protection (CP)
Corrosion
Galvanic anode
Impressed current system
Rectifier

ABSTRACT

Nuclear power plants have numerous structures that must be protected from external corrosion. Corrosion of a material is inevitable, but uncontrolled corrosion can increase maintenance costs and, in some instances, cause failure of structures, systems, and components.

Controlling corrosion in nuclear power plants can be accomplished through the proper selection and application of materials, coatings, and cathodic protection. Cathodic protection, when used in conjunction with protective coatings, can reduce the corrosion rate on a metal surface to an acceptable level so that adequate life of the structure can be provided.

With the effort in the nuclear power industry to maximize equipment life, it is important that plant operators understand the importance of corrosion control by cathodic protection in their life extension efforts. Cathodic protection can aid plant personnel in their endeavor to protect and maintain equipment in a safe and reliable manner.

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1
INTRODUCTION

Recent operating experience from nuclear power plants indicates that degradation of buried piping in at least some of the plants is becoming a maintenance issue. The vast majority of these plants, and particularly those in the United States, are now 30 to 40 years old. The design life of a typical impressed current cathodic protection (CP) system for buried piping is approximately 20 to 25 years. Many of the older CP systems at nuclear power plants have exceeded their original design life and now require upgrade, repair and/or replacement. Some of these systems may not be providing adequate levels of CP to control corrosion of the buried piping and corrosion related failures may increase unless appropriate measures are undertaken. The design and installation of new CP systems may also be required at plants where new piping systems have been installed, at plant areas where piping degradation has occurred, or at plants where CP was not initially used. To effectively manage the age of buried piping, it is important that plant engineering and maintenance staff focus time and effort on CP systems that are designed to control corrosion and consequently prolong the service life of buried piping systems, so that reliable operation of the plant equipment can be provided.

1.1 Scope and Purpose of the Guide

In order to plan and implement the appropriate maintenance methods to ensure adequate CP system performance, the type of system (impressed current or galvanic), design, materials selection, installation, testing and commissioning methods must be understood, documented and properly applied. This guide provides a systematic approach for the design, installation, testing, monitoring and maintenance of CP systems that are used for corrosion control of buried piping at nuclear power plants.

Corrosion can cause numerous problems that affect the integrity and capability of various structures, systems and components. For instance, piping systems can degrade and rupture as a result of corrosion. Also, structures such as storage tanks, ships, rail cars, tanker trucks, and nuclear waste facilities, all of which store and/or transport potentially hazardous materials, can be subject to the harmful effects of corrosion. When the structural integrity of equipment is weakened by corrosion, system function, plant operation, personnel safety, public safety and the environment can be threatened.

There are three (3) common methods used to control external corrosion of buried piping systems. These methods include proper material selection, protective coatings and cathodic protection:

> *Proper Material Selection* refers to the selection and use of corrosion-resistant materials such as stainless steels, plastics and special alloys to enhance the lifespan of a structure. Some of the most common materials used in construction, such as carbon steel and steel reinforced concrete, can be severely affected by corrosion.
>
> *Coatings* can be any mixture of film-forming materials, which when applied to a surface and cured or dried, provide a thin layer that protects the underlying material from

corrosion. Coatings are often applied in conjunction with CP systems to provide the most cost-effective method of protection for buried and immersed metallic structures.

Cathodic Protection (CP) consists of methods that use selected materials and the application of direct electrical current to counteract the normal external corrosion of a buried or immersed metallic structure. On new structures, CP can help prevent corrosion from occurring and for existing structures it can effectively reduce the rate of corrosion to an acceptable level.

This guide provides power plant staff with information for establishing an effective maintenance program for CP systems and components. The guide outlines the most common failure modes, describes appropriate predictive and preventive maintenance (PdM/PM) techniques, and provides information on the methods available to optimize service life and minimize maintenance costs through effective preventive maintenance and condition monitoring. Operating history, published literature, and the experience and expertise of numerous users and manufacturers were used in preparing this guide. Data sources include the following:

- Power plant maintenance, operating and engineering staff
- Cathodic protection system and equipment manufacturers
- Unified Facilities Criteria (UFC) Report No. UFC 3-570-06, *Operation and Maintenance: Cathodic Protection Systems*, January 31, 2003
- EPRI Report No. 1021470, *Balance of Plant Corrosion - The Buried Pipe Reference Guide*
- Final License Renewal Interim Staff Guidance LR-ISG-2011-03, *Changes to the Generic Aging Lessons Learned (GALL) Report*, Revision 2
- NACE International Standard Practices, Test Methods and Publications
- Results of an EPRI survey that was completed by nuclear power plant (NPP) staff, and
- Recommendations that are included in the EPRI Cathodic Protection GAP Analysis reports

Peabody's *Control of Pipeline Corrosion* is an excellent resource for power plant staff that are involved in the prevention and control of pipeline corrosion by cathodic protection.[1] A glossary of terms relating to corrosion and CP can be found in Appendix A of this guide. A complete list of standards, test methods and publications for CP of buried piping can be found in Appendix B.

Personnel using this guide should have a basic understanding of corrosion and cathodic protection principles for buried piping. The reader should be cognizant that the issues associated with CP and other corrosion control facets in a nuclear facility are markedly different than those associated with typical transmission and distribution piping systems in the petroleum, natural gas and water industries.

The provisions of this guide should be applied under the direction of competent persons who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by education and related practical experience, are qualified to engage in the practice of corrosion control on buried or submerged metallic structures. Such persons might be, but are not limited to registered professional engineers or persons certified by NACE as a Corrosion

[1] A. W. Peabody, *Control of Pipeline Corrosion*, 2nd Edition, 2001, NACE International, Houston, TX.

Specialist or CP Specialist, if their professional activities include suitable experience in external corrosion control for buried piping systems in plant environments.

1.2 Pop Outs

Throughout this guide, key information is summarized in Pop Outs. Pop outs are bold lettered boxes that succinctly restate information covered in detail in the surrounding text, making the key points easier to locate.

The primary intent of a pop out is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these pop outs was selected by the EPRI Project Manager, TAG members, and the author of this guide.

The pop outs are organized according to three categories: Operation and Maintenance (O&M) Cost, Technical, and Human Performance. Each category has an identifying icon, as shown below, to draw attention to it when quickly reviewing the guide.

Appendix C contains a listing of all of the key points in each category. The listing restates each key point and provides reference to its location in the body of the report. By reviewing this listing, users of this guide can determine whether they have taken advantage of key information that the author believes would benefit their plants.



Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.



Key Technical Point

Targets information that will lead to improved equipment reliability.



Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or to ease completion of the task.

2
CORROSION

NACE International defines corrosion as "the deterioration of a material, usually a metal that results from a reaction with its environment". Corrosion is an electrochemical process that is governed by electrical laws. Corrosion related damage is accelerated by factors such as differential soil aeration, differential soil chemistry, dissimilar metal contacts, stray direct currents and microbiological activity. Over time, uncontrolled corrosion can weaken or destroy structures or components, which could result in localized deterioration or possible structural failure.

Consideration of corrosion in the design, material selection, construction, operation and maintenance of structures and components saves billions of dollars in repair, maintenance and replacement costs. Controlling corrosion in the infrastructure can prevent premature failure and extend useful service life, both of which save money and natural resources, promote public safety, and protect the environment.



Key O&M Cost Point

Consideration of corrosion in the design, material selection, construction, operation and maintenance of structures and components saves billions of dollars in repair, maintenance and replacement costs.

A 2002 study backed by the U.S. Federal Highway Administration (FHWA) estimated that the annual costs of corrosion in the United States were $276 billion per year.[2] An earlier study published in 2001 by EPRI estimated the cost of corrosion in the electric power industry was $17 billion per year, representing about 7.9% of the cost of electricity in the United States.[3] Although these studies are now somewhat dated, the results indicate that corrosion impacts nearly every industry sector and that corrosion control programs, such as coatings and cathodic protection, remain a critical need in the United States.

Cathodic protection is an electrical method of mitigating corrosion through the application of an external direct current (DC). In general, CP can be defined as a technique that is used to control corrosion on a metal surface to an acceptable level [i.e., <25μm/y (<1 mpy)].[4] It is essential to understand the corrosion process to understand how cathodic protection works in reducing or preventing corrosion. This section briefly describes the theory behind corrosion of buried pipes and the effect that cathodic protection has on the corrosion process.

[2] Federal Highway Administration Report FHWA-RD-01-156, "Corrosion Costs and Preventive Strategies in the United States", 2002.

[3] EPRI Report 1004662, "Cost of Corrosion in the Electric Power Industry", 2001.

[4] NACE International Publication 35108, "One Hundred Millivolt (mV) Cathodic Polarization Criterion"

2.1 Electrochemical Corrosion

Buried pipes that are not adequately protected are usually subject to electrochemical corrosion. As shown in Figure 2-1, there are four (4) necessary components for an electrochemical corrosion cell:

- Anode - location where oxidation or corrosion occurs
- Cathode - location where reduction or corrosion protection occurs
- Electrolyte - electrically conductive media, such as soil, water or concrete, and
- Metallic path connecting the anode and cathode

The area of lower potential (more electro-positive) is the cathode and the area of higher potential (more electro-negative) is the anode. In order for an electrochemical corrosion cell to form, there must be a difference in potential between two different metallic structures or between one part of a metallic structure and another.

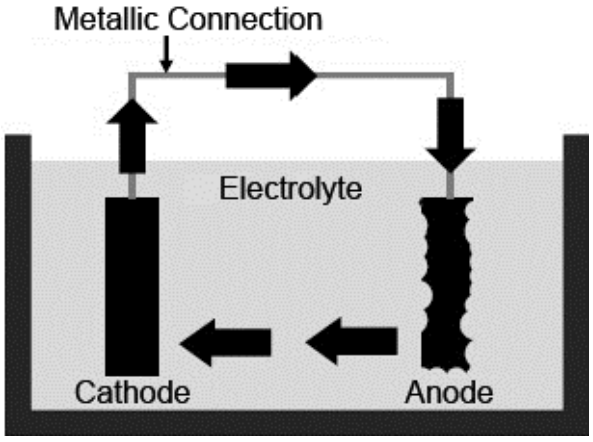


Figure 2-1
Electrochemical Corrosion Cell
(Source: UFC 3-570-06)

The anode and cathode must be in an electrically conducting medium or electrolyte. The electrolyte can be soil, water, concrete or any other chemically suitable material. When these conditions exist, direct current flows between the anode and cathode. The anode loses metal ions to the electrolyte and corrodes (or dissolves). The phenomenon is similar to that which takes place in a standard “dry cell” battery when it generates a direct current. The anode (negative electrode), cathode (positive electrode), the electrolyte (environment), and the external metallic circuit connecting the anode and cathode are required for corrosion to occur.

Key Technical Point

In order for an electrochemical corrosion cell to form, there must be a difference in potential between two different metallic structures or between one part of a metallic structure and another.

Electrochemical systems tend to change so that the free energy present is minimized. Metals are generally found in nature as an ore with low free energy. These ores are chemical compounds consisting of the metal atoms combined with other atoms such as oxygen or sulfur. The breakdown of ores into their metallic and non-metallic atoms involves the addition of energy to free the metal atoms. The corrosion process is driven by the tendency of these metal atoms to revert to their natural low energy state. Every metal immersed in an electrolyte develops an electrochemical potential due to the free energy of the atoms in the metal.



Key Technical Point

Every metal immersed in an electrolyte (soil, water, concrete or other electrically conductive material) develops an electrochemical potential due to the free energy of the atoms in the metal.

Cathodic protection utilizes a flow of direct current to control the corrosion process. In theory CP is defined as the reduction or elimination of corrosion by making the metal a cathode via an impressed direct current, or by connecting it to a sacrificial or galvanic anode. Cathodic areas in an electrochemical cell do not corrode. By definition, if all the anode sites were forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated; hence the term "cathodic protection".

Oxidation and reduction must occur together, i.e., when an atom or molecule is oxidized, another atom must be reduced. When metals with different potentials are in a common electrolyte a direct current flows between the anode and cathode sites. The anode loses metal ions to the electrolyte and corrodes.

To better understand the application of cathodic protection in corrosion control, the basic concepts of metallic corrosion in the presence of moisture are reviewed.

2.1.1 Basic Electrochemical Reactions

Oxidation is the loss of electrons from an atom or molecule and as a result, energy is released. Reduction is the gain of electrons by atoms and as a result energy is gained. Electrons function as energy carriers. When metals with different potentials are in a common electrolyte, a direct current flows between the anode and cathode and promotes corrosion of the anodic site.



Key Technical Point

Oxidation is the loss of electrons from an atom or molecule and as a result, energy is released. Reduction is the gain of electrons by atoms and as a result energy is gained. Electrons function as energy carriers.

Dissolution of metal occurs at the anode where the corrosion current enters the electrolyte and flows to the cathode (see Figure 2-1). The general reaction that occurs at the anode is the dissolution of the metal as ions:

$$M \rightarrow M^{n+} + e^{n-} \qquad \text{Eq. 2-1}$$

where:

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

In this reaction, the metal atom, which in combination with the other metal atoms, forms a piece of metal that is transformed into a metal ion that usually dissolves. This basic reaction shows that the 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 to occur.

At the cathode, chemical reduction occurs as follows:

$$R^+ + e^- \longrightarrow R^0 \qquad \text{Eq. 2-2}$$

where:

R^+ = positive ion in solution
e^- = electron
R^0 = reduced atom

The reduced atom may either be discharged as a gas or deposited on the cathode surface. The electrolyte serves as a medium for the deposition of the products of the chemical reactions, and a path for the flow of charged ions. In the electrochemical cell, a conducting path for electrons such as a metallic connection is required so that the electrons produced at the anode can flow to the cathode where they are absorbed.

In alkaline and neutral aerated soils, the predominant cathodic reaction is:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad \text{Eq. 2-3}$$

In aerated acidic soils, the cathodic reaction is generally:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad \text{Eq. 2-4}$$

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

2.1.2 Corrosion Initiation

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 aerated corrosive water, the anodic reaction would be:

$$Fe \rightarrow Fe^{++} + 2e^- \text{ (anodic reaction)} \qquad \text{Eq. 2-5}$$

At the cathode, the reduction of electrons with dissolved oxygen and the breakdown of water into hydroxyl ions would occur:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \text{ (cathodic reaction)} \qquad \text{Eq. 2-6}$$

Since, 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 combined anodic and cathodic reactions would be:

$$2Fe + O_2 + 2H_2O \rightarrow 2\,Fe^{++} + 4OH^- \qquad \text{Eq. 2-7}$$

After dissolution, ferrous ions (Fe^{++}) generally oxidize to ferric ions (Fe^{+++}) and these ions combine with hydroxide ions (OH^-) formed at the cathode to give a corrosion product referred to as rust (FeOOH or $Fe_2O_3 + H_2O$). These equations show that anodic dissolution of metal occurs electrochemically and the insoluble corrosion products are formed by a secondary chemical reaction.

2.2 Types of Corrosion Cells

A concentration corrosion cell is the result of the potential difference (electromotive force or EMF) caused by a difference in concentration of some component in the electrolyte. Any difference in the electrolyte that contacts the metal forms discrete anodic and cathodic regions on the metal. A metal exposed to these discrete electrolyte regions has a measurable potential or voltage difference. This potential difference causes the metal to develop anodic and cathodic regions. When there is also a metallic path, the circuit is complete, current flows, and electrochemical corrosion occurs.

Soil is an important factor in corrosion and cathodic protection of buried piping systems. There are many different types of soil, and even the same type of soil can vary greatly in its chemical composition and ionic concentration. Soil variations cause potential differences (electromotive force) on the metal surface resulting in electrochemical corrosion cells. Liquids tend to be more uniform, but the concentration of some components such as oxygen and salts can vary by depth and flow rates.

In nature, biological organisms are present in virtually all aqueous environments. Biological organisms tend to attach and grow on the surface of structural materials, resulting in the formation of a biological film. These biological films and the surrounding electrolyte are different and have many adverse effects. Common forms of concentration cell corrosion are discussed in the following paragraphs.

2.2.1 Dissimilar Soils Corrosion Cell

Pipes tend to be surrounded by many different types of soils. In nuclear power plants the backfill material around the buried piping can be extremely heterogeneous by virtue of the plant construction. The metallic piping material exhibits different electrical potentials in different soils. The electrical potential of the pipe surface in contact with the soils determines which areas become anodic and which areas become cathodic. Since both the anode and cathode are electrically continuous (the pipe serves as the metal path) and the electrolyte is in contact with both, current flows, resulting in oxidation and reduction reactions (corrosion and protection). The anodic area of the pipe corrodes.

Soil typically consists of horizontal heterogeneous layers. Pipes that are surrounded by several different types of soil that contain different materials such as rock, gravel, sand, loam, clay, or different combinations of these materials, which frequently tend to be affected by this type of corrosion. Pipe backfill materials may also contain debris and contaminants from construction activities, which can further damage the protective coating and provide localized concentration cells. Figure 2-2 is an example of a concentration cell caused by differential soils.

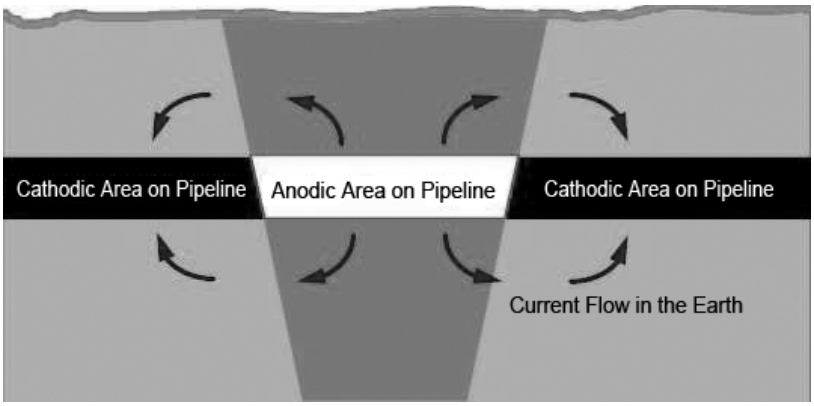


Figure 2-2
Concentration Cell Caused by Differential Soils
(Source: UFC 3-570-06)

Soils have been characterized for corrosion properties into general types. Different types of soils have different soil resistivity values. Dissimilar environment corrosion cells are generally formed where the soil resistivity values vary greatly in relatively short distances. These types of electrochemical corrosion cells are most serious when the anode is relatively small in area, soil resistivity is low and the open circuit potential is relatively high.

2.2.2 Differential Aeration Cell

The differential aeration cell is probably the most common corrosion cell found on buried pipes or other underground structures. In underground environments where the groundwater or soil is neutral or alkaline, the corrosion rate of buried metallic structures is primarily dependent on the oxygen concentration at the surface of the structure, and in turn depends largely upon the depth of the structure below grade and the diffusion of air through the soil to the metal surfaces. Oxygen enables a corrosion reaction by maintaining the cathodic reaction. Oxygen concentration normally decreases with depth in soils and will typically be lower at the base of a pipe compared to the top. Therefore on large diameter structures the base of the pipe is more likely to be anodic relative to the top which is cathodic. A similar situation may also exist where a buried pipe crosses beneath a paved access road. The pavement lowers the oxygen concentration in the soil and the piping beneath the road will become the anode in the differential aeration cell. In these regions current leaves the metal surface, increasing the corrosion rate, and flows to the cathodic areas on the pipe where the oxygen concentration is higher. A similar differential aeration cell may also exist at the air-to-soil interface where the piping exits the ground. Dry conditions near the soil surface can often prevent CP current from reaching the piping in these areas.

Piping that is exposed to a soil with a low oxygen concentration is shown in Figure 2-3. This condition is most severe when a pipe is placed on the bottom of an excavation and backfill is placed around the remaining part of the pipe. During the excavation and backfill operation, the backfill is exposed to oxygen. As a result, the backfill may contain a relatively high amount of oxygen compared to the undisturbed earth beneath. This effect may be somewhat reduced in areas where the soil is highly compacted.

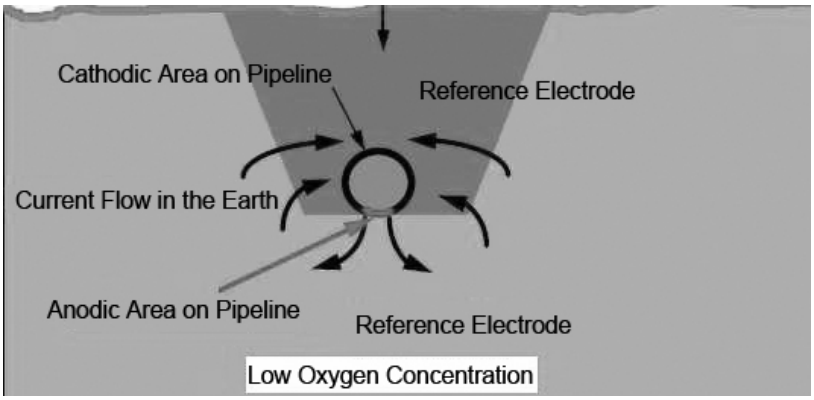


Figure 2-3
Differential Aeration Concentration Cell
(Source: UFC 3-570-06)

2.2.2.1 Moist/Dry Electrolyte

Pipes that are exposed to soils with low and high moisture content will tend to exhibit different electrochemical potentials in these areas. Generally, the area of the pipe that is exposed to soil with higher moisture content will become anodic relative to the area with lower moisture content.

2.2.2.2 Non-Homogeneous Soils

Structures that are exposed to a non-homogenous electrolyte exhibit different electrical potentials in different components of the soil. This is most severe when a pipe is placed in soils that have large variations in their composition, which cause large potential differences. The soil can become non-homogeneous by the introduction of backfill impurities. Backfill impurities are foreign materials that are mixed into the soil during or between the excavation and the backfill process.

2.2.3 Concrete/Soil Interface

Structures that are in contact with concrete and are exposed to another electrolyte, such as soil, will exhibit different potentials in each area as shown in Figure 2-4. Piping that is in contact with concrete and soil may create a corrosion cell, as a result of the high potential difference caused by the variation in electrolyte resistivity. The area not in contact with concrete becomes anodic to the area inside the concrete. Carbon steel piping that enters concrete vaults and building foundation walls may experience this condition.

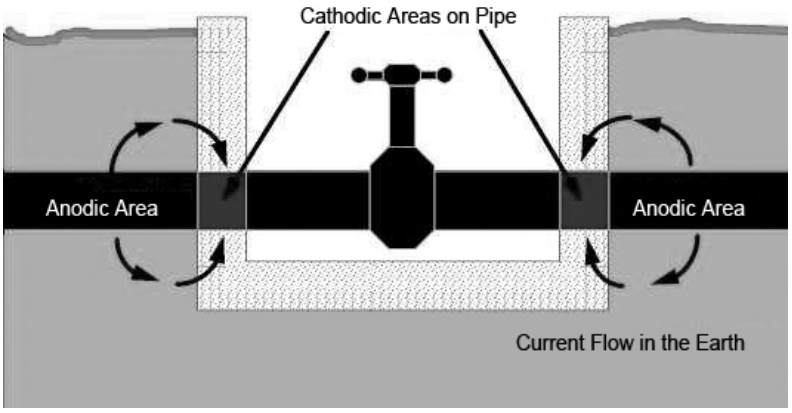


Figure 2-4
Concentration Cell Caused by Concrete and Soil Electrolytes
(Source: UFC 3-570-06)

2.2.4 Microbiologically Influenced Corrosion

Micro-organisms are present everywhere in soils, freshwater, seawater and air. Microbiologically Influenced Corrosion (MIC) is an aggressive form of corrosion caused by the presence or activities of microorganisms. Bacteria, fungi and other microorganisms can play a significant role in soil corrosion resulting in a broad range of outcomes including accelerated pitting attack, crevice corrosion, differential aeration cells, metal concentration cells, selective de-alloying, under-deposit corrosion and enhanced galvanic corrosion. In un-aerated or anaerobic soils, this attack is generally attributed to the influence or presence of sulfate-reducing bacteria (SRB). This type of mechanism is believed to involve both direct attack of the steel (metal surface) by hydrogen sulfide and also cathodic depolarization. Even in aerated or aerobic soil conditions, there are sufficiently large variations in aeration that the action of SRB on a buried steel pipeline cannot be discounted. For example, even within an active corrosion pit or under a bacterial biofilm, the oxygen content can become exceedingly low.

The most aggressive form of MIC typically takes place in the presence of microbial consortia that are comprised of many different types of bacteria. Depending on the environment, these microbes may include metal-oxidizing bacteria (MOB), exopolysaccharide (EPS) producing bacteria, acid-producing bacteria (APB), metal-reducing bacteria (MRB) and SRB that interact in complex ways within a structure to produce biofilms. The conclusion that MIC is involved in the corrosion of buried pipe in soil should be based on the presence of circumstantial evidence, including examination of the pit morphology and proper collection and testing of solid corrosion product samples (i.e., rust, surface scale, nodules and biofilm, etc.). Field kits are available for qualitative tests of chemical species; however for accurate assessment of microbial involvement, laboratory analysis of the samples for the number of viable bacteria should be performed using media bottles from testing apparatus. Exposure of the pipe for site inspection and sample collection for MIC analysis should be slow and careful, so as to avoid damage to the pipe coating, the affected surface and areas of sampling. Corrosion products should be collected and analyzed for color, shape and texture. Special precautions should be taken when removing samples from the pipe surface for testing, as significant changes in the detectable numbers and types of microorganisms can occur rapidly after removal of samples from the environment. Ideally samples should be processed and the results analyzed immediately after collection. Interpretation of analytical results from samples obtained from corroded areas should be

compared to samples taken outside the corroded area. Increased levels of viable bacteria associated with pit areas are often good indicators of microbial involvement, although the actual corrosion is dependent on the microbial activity and not population. However, determining the cause of external corrosion on a buried pipe requires that all chemical, microbiological, metallurgical and operational data be examined.

After collection of the samples for testing, the coating should be removed in the affected area and the pipe surface cleaned using abrasive blasting or other approved methods to allow thorough examination of the pipe surface for corrosion damage. Pit morphology as a result of MIC may include dish or cup-shaped pits with sharp edges, pits within a pit, and striations on the metal surface (see Figure 2-5). Corrosion products may be in the shape of tubercles and have characteristic citric and sour odors, and pasty consistency if active.

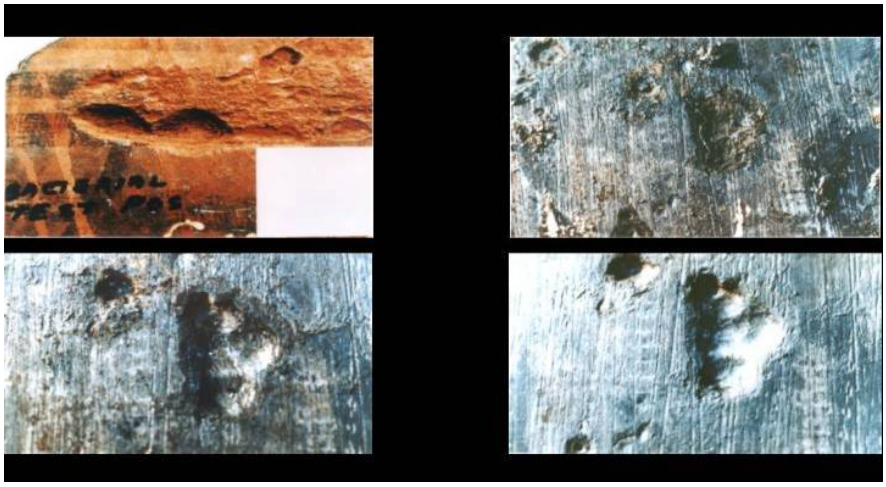


Figure 2-5
Examples of Microbiologically Influenced Corrosion (MIC)

Microorganisms are often resistant to many control methods and can be a serious threat to buried piping, especially those that have poor quality coatings or cathodic protection systems that are not properly maintained. Piping subject to MIC activity may have CP requirements that are 100 to 200 mV more cathodic compared to conditions where MIC is absent due to the presence of microbially generated sulphides. Research by Barlo and Berry showed that a pipe-to-soil potential of at least -950 mV to a copper-copper sulfate reference electrode (CSE) is required to mitigate corrosion on pipelines that are susceptible to MIC, as opposed to the standard NACE criterion of -850 mV (CSE).[5] NACE TM0106-2006 provides a standard test method for the detection, testing and evaluation of MIC on the external surfaces of ferrous based pipelines.

Key Technical Point

Research has shown that a pipe-to-soil potential of at least -950 mV (CSE) is required to mitigate corrosion on pipelines that are susceptible to MIC.

[5] T.J. Barlo, W. E. Berry, "An Assessment of the Current Criteria for Cathodic Protection of Buried Steel Pipelines," *Materials Performance* 23, 9 (1984).

2.2.5 Dissimilar Metal Corrosion

Dissimilar metal corrosion can occur when two different kinds of metal (such as copper grounding and carbon steel piping connected into other metals) are immersed or buried in a common electrolyte and metallically bonded or shorted as shown in Figure 2-6.

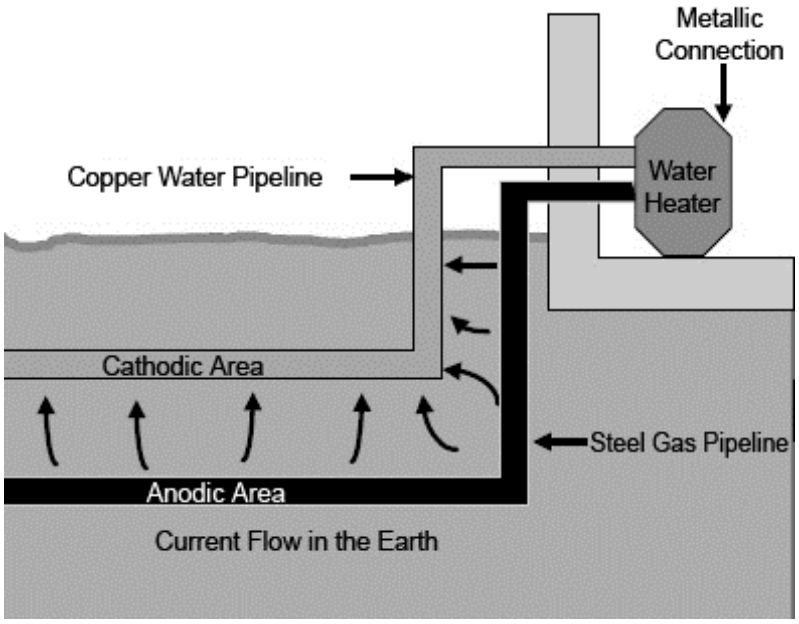


Figure 2-6
Galvanic Corrosion Cell Caused By Dissimilar Metals
(Source: UFC 3-570-06)

A corrosion cell is established when two dissimilar metals are metallically bonded or shorted in some manner and in contact with the same electrolyte. Dissimilar metal corrosion is most severe when the potential difference between the two metals i.e., driving voltage is the greatest, cathode/anode area ratios are high, and the resistivity of the electrolyte is relatively low. Table 2-1 is a practical galvanic series for a number of metals that are typically used in power plants. The relative position of the metals by virtue of their electromotive force will determine which metal will corrode relative to the other. In a dissimilar metal corrosion cell the metal with the more negative potential will become the anode and corrode. For example, if a direct buried carbon steel pipe were in contact with carbon steel pipe encased in concrete from exiting a building, the buried carbon steel pipe would corrode. Similarly if stainless steel pipe were tied to carbon steel pipe, the carbon steel would corrode. The galvanic series of metals is generally used to identify materials of widely different voltages so that their use in combination can be avoided. If combinations of metals with widely different voltages cannot be avoided, then appropriate measures need to be put in place to mitigate dissimilar metal corrosion.

Table 2-1
Practical Galvanic Series for Materials in Neutral Soils and Water
(Source: Peabody's Control of Pipeline Corrosion, 2nd Edition, NACE International)

Material	Potential Volts (CSE)*
Carbon, Graphite, Coke	+0.3
Platinum	0 to -0.1
Mill Scale on Steel	-0.2
High Silicon Cast Iron	-0.2
Copper, Brass, Bronze	-0.2
Mild Steel in Concrete	-0.2
Lead	-0.5
Cast Iron (Not Graphitized)	-0.5
Mild Steel (Rusted)	-0.2 to -0.5
Mild Steel (Clean and Shiny)	-0.5 to -0.8
Commercially Pure Aluminum	-0.8
Aluminum Alloy (5% Zinc)	-1.05
Zinc	-1.1
Magnesium Alloy (6% Al, 3% Zn, 0.15% Mn)	-1.6
Commercially Pure Magnesium	-1.75

* Typical potential normally observed in neutral soils and water, measured with respect to a copper-copper sulfate reference electrode (CSE).

2.2.6 Old-to-New Pipe Syndrome

Old-to-new pipe corrosion can be rather severe. The process of producing steel requires a very high input of energy. This high level of energy input to produce new steel suggests that new steel is more active than corroded steel. The potential difference between the high negative potential of the new steel and the low negative potential of the old steel is the driving force, or voltage, of this electrochemical corrosion cell as shown in Figure 2-7. A common example of this type of corrosion is when an old bare steel pipe fails, and a small section of the old steel pipe is replaced with a new steel pipe. Because of the large negative potential relative to the old corroded steel, the new section becomes the anode and corrodes to protect the larger cathode, resulting in failure of the new section of pipe.

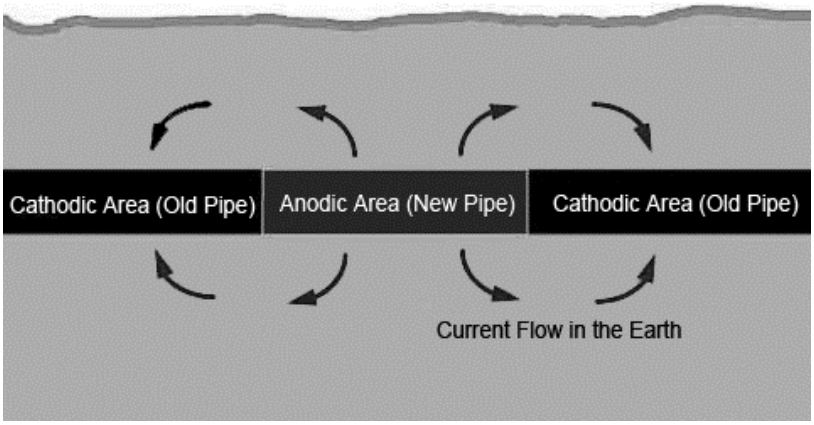


Figure 2-7
Galvanic Corrosion Cell Caused By Old and New Steel
(Source: UFC 3-570-06)

2.2.7 Marred or Scratched Surfaces

A marred or scratched surface on a pipe may become anodic to the surrounding metallic surface. This is similar to the old-to-new pipe syndrome, where new steel is anodic to the old steel. An electrochemical corrosion cell is caused by the potential difference between the scratched surface exposing new material and the remaining surface of the structure. Some of the examples of this type of electrochemical corrosion cell are threaded pipe, bolts, and marks from tools. Corrosion in these areas is caused by pipe wrenches and other tools, and marks from shovels and backhoes are common examples of this type of electrochemical corrosion cell. This situation is further aggravated because the metal thickness is also reduced in these areas (see Figure 2-8).

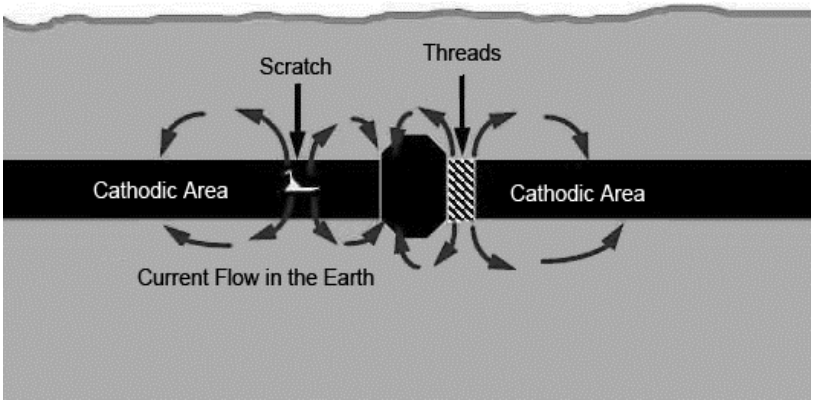


Figure 2-8
Galvanic Corrosion Cell Caused by Marred and Scratched Surfaces
(Source: UFC 3-570-06)

2.2.8 Environmental Factors

Environmental factors such as elevated temperatures can increase the rate of corrosion. Metals at an elevated temperature become anodic to the same metal at a lower temperature. As previously discussed, a more active metal is anodic to a more noble metal. This electrochemical corrosion cell may cause accelerated corrosion on metals that are at elevated temperatures.

2.2.9 Stray Current Corrosion

Stray current corrosion occurs where the current from the external source leaves the metal structure and enters back into the electrolyte, normally near an external power source. The external power source is the driving force of the cell. Stray currents are either static (non-varying) or dynamic (varying). Stray current corrosion is different from natural corrosion because it is caused by an externally induced electrical current and is basically independent of such environmental factors as concentration cells, resistivity, pH and galvanic cells.

Stray current is typically not a concern at nuclear power plants because the common grounding provides electrical continuity between structures. Nevertheless stray current can result from a grounded DC system, a welding machine, or a cathodic protection system operating on a nearby foreign pipeline or structure. Generally, the most adverse stray current effect in a power plant occurs when an impressed current cathodic protection system is installed on a pipeline adjacent to an electrically isolated foreign pipeline (See Figure 2-9). Because the foreign pipeline is not electrically connected to the cathodically protected pipeline and is located within the voltage gradient of the system, cathodic protection current is picked-up and discharged from the isolated structure. Severe corrosion can occur at the point where current discharges into the electrolyte. The potential gradient in the electrolyte forces one part of the structure to pick-up current (become cathodic) and another part of the structure to discharge current (become anodic).

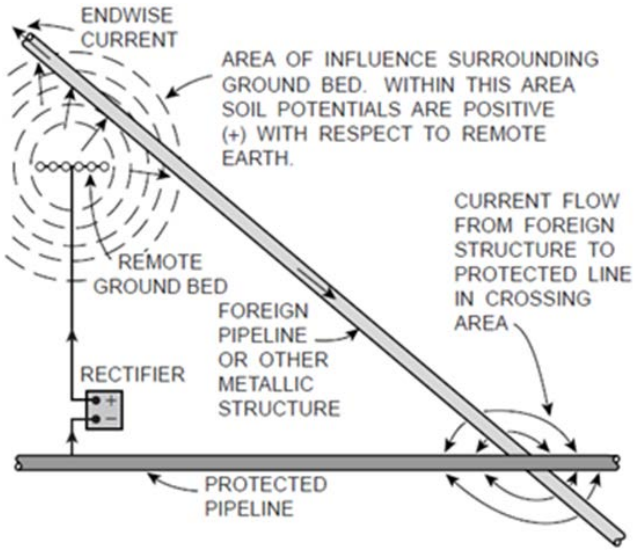


Figure 2-9
Stray Current Corrosion on Electrically Isolated Foreign Pipeline
(Source: Peabody's Control of Pipeline Corrosion, 2nd Edition, NACE International)

Stray current corrosion can be extremely severe because of the large amount of current that will be forced into the soil from the external DC power source. The metallic structure becomes an anode and the amount of current discharging into the electrolyte translates directly into metal loss. If the amount of current leaving a structure to enter the electrolyte can be measured, this can be directly translated into metallic weight loss. Different metals have specific amounts of weight loss when exposed to current discharge. This weight loss is normally measured in pounds (or kilograms) of metal lost due to a current of one amp for a period of one year (one amp-year). For example, if a stray current of just two amps was present on a steel pipe, the result would be a loss of 40.2 pounds (18.2 kilograms) of steel in one year. For a coated pipe, this could result in a

penetration at a defect in the coating in an extremely short period of time, sometimes in only a few days. Table 2-2 provides consumption rates for various metals. Large stray currents usually require special analysis and corrective measures.



Key Technical Point

Different metals have specific amounts of weight loss when exposed to current discharge. This weight loss is normally measured in pounds (or kilograms) of metal lost due to a current of one amp for a period of one year (one amp-year).

Table 2-2
Weight Loss of Metals at a Current of One Ampere for One Year (1 Amp-Year)
(Source: UFC 3-570-06)

Metal (Ion)	Weight Loss (Kilograms)	Weight Loss (Pounds)
Cadmium	18.39	40.5
Carbon (C+)	1.91	4.2
Carbon (C++++)	1.00	2.2
Chromium	5.65	12.5
Cobalt	9.63	21.2
Copper (Cu+)	20.77	45.6
Copper (Cu++)	10.39	22.8
Iron (Fe++)	9.13	20.1
Lead (Pb++)	33.87	74.5
Magnesium	4.00	8.8
Aluminum	2.95	6.5
Nickel	9.58	21.1
Silver	35.2	77.6
Tin	19.39	42.7
Zinc (Zn++)	10.66	23.6

2.2.10 Simultaneous Sources of Corrosion

Each of the above types of electrochemical corrosion cells may cause significant corrosion, but in many cases a combination of different types of corrosion simultaneously work to make corrosive situations even worse on the metal surface (see Figure 2-10). Understanding the actual cause of corrosion is of utmost importance in maintaining a submerged or buried metallic structure, such as a pipe or storage tank.

When corrosion is noted, or when a leak occurs due to corrosion, it is essential that the root cause of corrosion is identified so that the appropriate corrective action can be taken. Often one or more actions are occurring simultaneously which results in corrosion (i.e., coating holiday, low resistivity soil, copper grounding in close proximity to pipe). Once the types of corrosion are understood, the method of repairing can be determined and future leaks can be prevented. In many cases, the location of the anodic area can be predicted by understanding the process of corrosion. These anodic areas tend to be in the worst possible places such as pipes entering pits or foundations, pipes under stress, or pipes at elevated temperatures.

Key Technical Point

When corrosion is noted, or when a leak occurs due to corrosion, it is essential that the cause(s) of the corrosion be identified so that the appropriate corrective action can be taken.

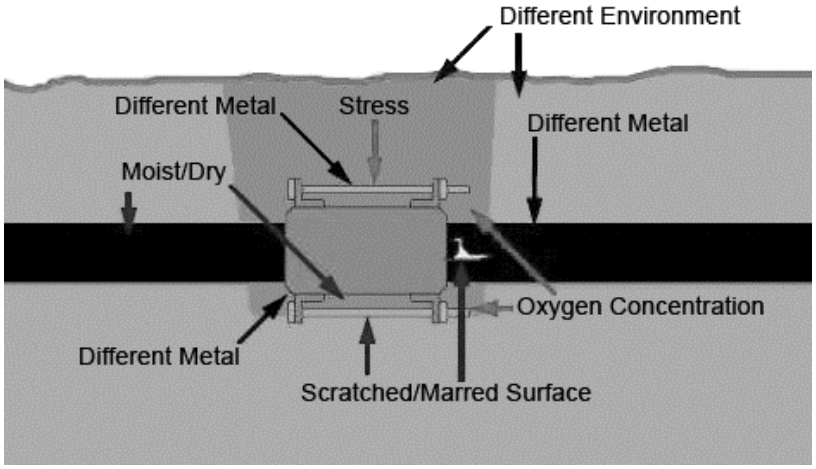


Figure 2-10
Simultaneous Corrosion Cells at Work
(Source: UFC 3-570-06)

2.3 Soil Corrosivity

Soil is composed of particles of broken down rock that have been altered by chemical and environmental processes that include weathering and erosion. Soil is an aggregate of essentially four constituents: (1) mineral particulates, (2) organic matter from the surface and subsurface, (3) groundwater containing soluble salts, and (4) gases. The proportions of the basic constituents vary greatly in different soil types. The particulate matter that is found in soils is usually small particles of the minerals from nearby rock formations, which consists mostly of insoluble minerals, as the soluble species have been removed by weathering over millions of years. The solubility of these minerals may vary with pH and will tend to buffer the pH of the groundwater.

Soil as a backfill for buried nuclear piping may be native material taken from the pipe excavation or plant site, and/or imported fill that was obtained from a local quarry or other source. Backfill at nuclear power plants normally has a controlled composition and size distribution (engineered

backfill). Backfills may also be cementitious in nature, such as flowable fill. Pipes that are embedded in concrete or flowable fill will benefit from the high alkalinity of the Portland cement. The high pH will reduce the corrosion rate of the steel and help reduce the current requirement for cathodic protection. Although the flowable fill will usually be higher in resistivity than the surrounding soil, it should be sufficiently conductive to pass cathodic protection current to the pipe surface. Flowable fill may however affect the current distribution from cathodic protection anodes when used sporadically as a backfill material around the piping.

The corrosivity of soils varies over a wide range because of the variety of compositions. Tests in one location are generally applicable only to that location and tests of several years' duration are needed to obtain reliable data, as conditions can vary with the season, rainfall, and as minerals from surrounding soil leach into the backfill. Factors affecting the corrosiveness of soils include moisture, alkalinity, acidity, permeability of water and air (compactness or texture), oxygen, salts and microbiological organisms. Many of these factors affect the electrical resistivity of soil, which is a good measure of corrosivity. However the magnitude and/or degree of soil corrosivity may not be a concern if adequate CP is applied and maintained over the life of the structure.

2.3.1 Moisture Content

Water constitutes the essential electrolyte that supports the electrochemical process of corrosion in soil. Groundwater is important in this regard, as the elevation of groundwater fluctuates from area to area. The test method for determining moisture content in soil is based on removing soil moisture by oven-drying a soil sample until the weight remains constant. The moisture content (%) is calculated from the sample weight before and after drying. The water-holding capacity of a soil is strongly dependent on its texture. Coarse sands retain very little water, whereas fine clay soils tend to store water to a higher degree. Soils with high moisture content will typically have a lower resistivity and therefore are considered more corrosive to buried metallic structures. Ideally anode groundbeds for cathodic protection should be located in soils with higher moisture content. Table 2-3 provides the effect that moisture content has on soil resistivity.

Table 2-3
Effect of Moisture Content on Soil Resistivity
(Source: IEEE, Green Book, 1982)

Moisture Content (% by weight)	Resistivity (ohm-cm)	
	Top Soil	Sandy Loam
0	>1000 x 106	>1000 x 106
2.5	250,000	150,000
5	165,000	43,000
10	53,000	18,500
15	19,000	10,500
20	12,000	6,300
30	6,400	4,200

2.3.2 pH

The term pH is a measure of the alkalinity or acidity of an electrolyte, ranging from highly alkaline at 14 to highly acidic at zero, with neutrality at 7. It is the negative logarithm of the hydrogen ion concentration. Acidic soils (lower pH) are typically aggressive with respect to buried metallic structures. As the pH increases to greater than 7 (the neutral value), conditions become increasingly more alkaline and less corrosive. Alkaline conditions do not pose any serious threat to carbon and stainless steel pipelines. Soil pH should be measured using the test methods described in ASTM Designation: G-51(2005). Table 2-4 provides an outline showing the degree of corrosivity for buried carbon steel pipelines with respect to soil pH.

Table 2-4
Soil pH Classification for Carbon Steel
(Source: Romanoff, M., Underground Corrosion, 1982)

Soil pH	Degree of Corrosivity
<5.5	Severe
5.5 - 6.5	Moderate
6.5 - 7.5	Neutral
>7.5	None (alkaline)

2.3.3 Soil Resistivity

Electrical resistivity is the measure of how strongly a material opposes the flow of electrical current. Resistivity has historically been used as an indicator of soil corrosivity. Since ionic current flow is related to soil corrosion, soils with low resistivity will usually increase corrosion reactions. However soil resistivity is by no means the only parameter affecting risk of corrosion, and soils with high resistivity will not guarantee the absence of corrosion. Macro-corrosion cells may be formed along a pipe where large variations in soil resistivity are encountered. The SI unit of electrical resistivity is ohm-meter (to convert ohm-m to ohm-cm multiply by 100). Soil resistivity is typically measured using the Wenner 4-Pin method in accordance with ASTM Standard G57. The Wenner method requires the use of four metal pins or electrodes, driven into the soil along a straight line equidistant from each other. To avoid inaccurate readings care should be taken to avoid influence from buried structures that are beneath the pins or in close proximity to the pins. Ideally the array should be positioned perpendicular to the buried piping so that buried structures are remote by a factor greater than 1.5x the pin spacing. Due to the complexity of buried structures within a plant, soil resistivity measurements using the Wenner method may be limited to open areas outside of the protected area (PA).

Other methods for soil resistivity measurement include the Colin's Rod method (single-electrode probe) and the soil box method. When using the soil box method, soil samples are taken from representative excavations or bore holes and measured for resistivity. The soil should be well-compacted in layers in the soil box and filled so the soil is flush to the top of the box. Air spaces and voids should be minimized when soil is compacted within the box.

Ideally anodes for cathodic protection should be located in soils with lower soil resistivity so that a low anode-to-soil resistance is provided. Table 2-5 is a classification prepared by DNV for determining the corrosivity of soils and water as a function of resistivity.

Table 2-5
Soil and Water Resistivity Classification

Soil and Water Resistivity	Classification
<500 ohm-cm	Extremely Corrosive
500 to 1,000 ohm-cm	Very Corrosive
1,000 to 10,000 ohm-cm	Corrosive
10,000 to 20,000 ohm-cm	Moderately Corrosive
>20,000 ohm-cm	Progressively Less Corrosive

2.3.4 Redox Potential

Redox potential is a measure of a material to acquire electrons and thereby be reduced. It is essentially the measure of the degree of aeration in a soil. A high redox potential (>100 mV) indicates a high oxygen concentration. Low redox values (<100 mV) indicate low oxygen concentration and provide an indication that conditions are conducive to anaerobic MIC activity. Sampling of soils will lead to oxygen exposure and therefore unstable redox potentials are likely to be measured in undisturbed soil. Redox potential should be measured in accordance with ASTM G200.

2.3.5 Chlorides

In general chloride ions participate in the dissolution reactions of many metals and furthermore their presence tends to decrease soil resistivity. Chlorides may be found naturally in soils as a result of brackish groundwater or ancient sea beds, or from de-icing salts that are applied to roadways in colder climates. For steel pipelines the chloride ion tends to breakdown the otherwise protective surface deposits and can result in corrosion and corrosion pitting of buried metallic structures. Table 2-6 correlates the effect that chlorides have on corrosion of buried steel pipelines.

Table 2-6
Effect of Chlorides on Corrosion of Buried Steel Pipelines
(Source: Peabody's Control of Pipeline Corrosion, 2nd Edition, NACE International)

Chloride Concentration (ppm)	Degree of Corrosivity
>5,000	Severe
1,500 – 5,000	Considerable
500 – 1,500	Corrosive
<500	Threshold

2.3.6 Sulfates

Sulfate ions are generally considered to be more benign compared to chlorides in their reaction to corrosion activity of steel pipelines in soil. However concrete can be attacked as a result of high sulfate ion concentrations. The presence of sulfates in soils can pose a direct risk to

corrosion of buried steel pipelines since these ions are nutrients for sulfate reducing bacteria (SRB), which convert these ions into highly corrosive sulfides.

2.4 Impact of Electrical Grounding

Buried pipes at nuclear power plants are interconnected to reduce the effects of hazardous voltages associated with lightning and fault currents in the earth. If not grounded the piping could become a touch hazard in the event of a lightning strike or an equipment ground fault. Insulating devices that provide electrical isolation of buried piping systems for cathodic protection are typically not installed in nuclear power plants and if present are usually shorted through external connections. Because of the dissimilar metal couplings that exist in the soil through the common grounding, corrosion rates can significantly increase on some of the buried structures. When materials such as cast iron and carbon steel are interconnected in the soil, they are very close in the galvanic series of metals and each suffers very little additional corrosion as a result of the couple. However, creating a dissimilar metal couple by connecting carbon steel to copper, stainless steel or reinforcing steel in concrete can form a very significant corrosion cell.

Buried metallic pipes at nuclear power plants may be constructed of several different materials including: carbon steel, stainless steel (series 300 and super austenitic), titanium, aluminum, galvanized steel, cast iron, corrugated metal, copper alloys and prestressed or reinforced concrete. Carbon steel is often used for buried piping in nuclear power plants. These pipes may consist of large diameter lines that transport circulating water and/or service water. The practical galvanic series for materials in neutral soils and water is given in Table 2-1. The more noble metals, and especially copper, are electro-positive with respect to carbon steel. The native potential of clean mild steel in neutral soils and water can range between -500 and -800 mV with reference to a copper-copper sulfate electrode (CSE), whereas the typical potential of copper is normally observed to be -200 mV (CSE). The galvanic series indicates that when copper is electrically coupled to mild steel in soil, the copper will become the cathode and the steel will become the anode, accelerating corrosion of the steel. The driving voltage between the two metals (mild steel and copper) can often be as high 0.3 to 0.5 Volts. The resulting pipe-to-soil potential is therefore a mixed potential of different materials (e.g., copper, cast iron, ductile iron, galvanized steel, stainless steel and carbon steel), and is often more depressed (more electro-positive) than the native potential of steel.

Carbon steel piping at nuclear power plants is typically coated with coal tar enamel or epoxy. The coating may have been damaged during construction or often has degraded over time, resulting in voids or holidays in the coating where corrosion can concentrate. When coated carbon steel pipe is tied directly to more noble metals, such as copper that is cathodic to steel, accelerated corrosion can occur at the coating holidays. This can result in a small anode/large cathode area relationship, where the smaller anode (exposed carbon steel at the coating flaw) is subject to a high density of current discharge per unit area, with the total amount of current governed by the kinetics of the oxidation and reduction reactions and the resistivity of the electrolyte (soil). The galvanic corrosion cell is most acute in low soil resistivity environments where the copper grounding is in close proximity to the coated carbon steel pipeline and small holidays are evident in the coating. Under this condition, the corrosion cell developed from the coupling is under mixed or anodic control, and concentrated corrosion can be expected at the holidays in the coating. This condition is shown is shown in Figure 2-11. If, on the other hand, the anodic area is large compared to the cathodic area, corrosion will be relatively mild.

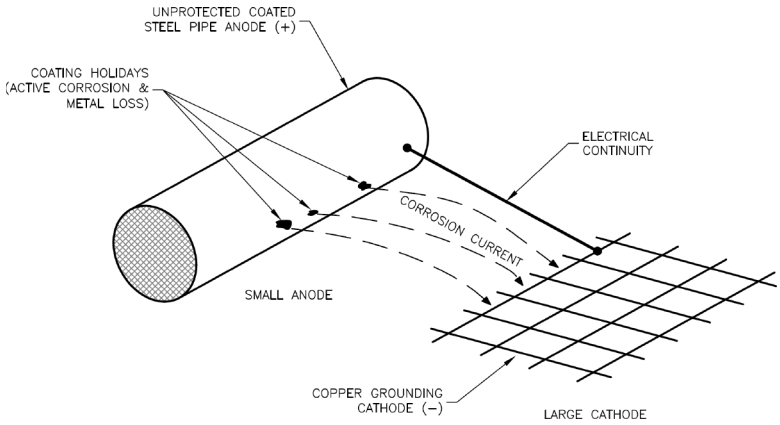


Figure 2-11
Concentrated Corrosion at Coating Holidays in Carbon Steel Pipe without CP

A dielectric coating system for the buried pipelines serves as the first line of defense against corrosion. The coating provides a corrosion control barrier between the pipe surface and the local soil or water environment. Cathodic protection is used to supplement the coating and provides corrosion control to the piping at flaws or "holidays" in the coating. The combination of dielectric coatings and CP generally produces an effective corrosion control system with minimal current demands if the pipe is fitted with insulating devices. As stated earlier, insulating devices are typically not installed in the piping and if present are bi-passed (shorted) by external connections. Therefore most of the CP current will be received or "picked-up" on the surrounding metallic structures that are not intended for CP. Due to the size of the grounding grid, the formation of the galvanic couple between the copper and steel and the tendency of current to preferentially travel to ground along the copper conductors, the current requirement for cathodic protection of buried piping at nuclear power plants will be much larger compared to an electrically isolated piping system. It is not uncommon for CP systems at nuclear plants to have a design capacity in excess of 1,000 amperes of direct current to cathodically protect the extensive network of piping, whereas for piping that is electrically isolated the current requirements could be substantially less.[6]

The design of a cathodic protection system for grounded pipe is further complicated because the corrosion rate of copper may be greater than that of iron or steel in the same environment. In addition copper does not polarize as readily as steel. Waters has reported that copper water piping required current densities ranging from 0.23mA/ft^2 to 4.08mA/ft^2 (0.25μA/cm^2 to 4.4μA/cm^2) after a 9 month period.[7] Furthermore, Kirkpatrick has stated that the "current density required to polarize the copper to an adequate potential necessary to protect a ferrous structure may be 10 to 20 times as high, on a per unit basis".[8] Gummow has reported that in non-aerated soils, copper clad steel ground rods that would normally be cathodic to steel, require the same or less current to adequately polarize steel. However in more aerated sandy soil, the current

[6] Daily, S.F., "Cathodic Protection Design Considerations for Buried Nuclear Piping", NACE Corrosion/2011, Paper No. 11182.

[7] Waters, D.M., "Cathodic Protection to Protect Copper Pipelines from External Corrosion," NACE Corrosion/82, 1982, Paper No. 41, p.15.

[8] Kirkpatrick, E.L., "Electrical Grounding and Cathodic Protection Issues in Large Generating Stations," *Materials Performance*, November 2001, p. 18.

requirements for copper clad steel increased by 3 orders of magnitude when compared to steel.[9] Copper grounding can therefore have a significant effect on the overall current requirement for cathodic protection of buried pipes in nuclear power plants. This overall increase in current demand may have a significant cost implication in terms of the design, installation, monitoring and maintenance requirements for CP systems. The installation of insulating devices (with DC decouplers) can reduce this high CP current demand.

The reinforcing steel bars in concrete foundations at power plants are typically bonded and grounded. Reinforcing steel in concrete tends to be noble (electro-positive) with respect to steel in soil because of the passive layer that develops on the rebar surface as a result of the high alkalinity of the portland cement. In new reinforced concrete structures, the structure-to-electrolyte potential of mild reinforcing steel can often range between 0 and -200 mV (CSE), resulting in a large galvanic couple when tied to carbon steel. Steel sleeves are typically used where the buried pipe enters a building foundation wall. The sleeves and carrier pipe are grounded to the reinforcing steel in the concrete. The potential of the buried pipe will usually be depressed at the entry point through the wall as a result of the coupling to the rebar and copper grounding that exists around the perimeter of the building. Since the corrosion cell can be quite significant at building foundation walls, these areas of pipe are often the most difficult to cathodically protect. Often these areas may require the installation of supplemental anodes and additional monitoring (test stations) near the building wall entry point.

2.5 Corrosion of Prestressed Concrete Cylinder Pipe

The most common type of prestressed concrete cylinder pipe (PCCP) is embedded cylinder pipe (ECP) that conforms to AWWA C301. ECP is easily identified by the high strength wire that is embedded in the concrete lining between two layers of concrete and presents a unique challenge with respect to corrosion of the wire. Most failures of PCCP pipelines involved ECP. A study sponsored by the AWWA Research Foundation and US Environmental Protection Agency (EPA) found that most ECP pipe failure problems were from the same pipe manufacturer and could be traced to an in-house wire production facility.[10] Most of the problem pipe was manufactured between 1970 and 1981 using Class IV prestressing wire.

The high strength tensile steel wires are susceptible to corrosion and failure if the high alkalinity of the concrete and mortar is compromised by either carbonation or chloride ingress from the soil (normally the pH of concrete and mortar ranges between ~ 12.5 and 13.8). Carbonation involves the reaction of atmospheric carbon dioxide with hydroxides to form carbonates, and the pH is reduced below the value for which steel is passive. Chlorides, on the other hand, arise from exposure of the concrete to deicing salts, a marine environment, high-chloride soils and ground waters. Although chlorides do not significantly alter pH of the concrete pore water, they do react with and locally compromise the passive film on the prestressing wire surface.

[9] Gummow, R.A., "Cathodic Protection Current Requirements for Electrical Grounding Materials," NACE Corrosion 2004, Paper No. 04045, p.1 and 7.

[10] *Failure of Prestressed Concrete Cylinder Pipe*, AWWA Research Foundation and US Environmental Protection Agency, 2008.

2.6 Rate of Corrosion

Corrosion of buried pipes is primarily electrochemical in nature. Anything that affects the speed of the chemical reaction will in turn affect the amount of current flow, which will affect the rate of corrosion. If the current can be measured accurately, then an exact calculation of the metal loss can be made. Therefore a measurement in amperes or milliamperes can be mathematically translated directly into pounds (kilograms) of material consumed per amp per year. Therefore one amp-year is equivalent to one ampere of current flowing for a period of one year. The consumption rate of different metals is given in Table 2-2.

The most commonly used expression for corrosion rate in the US is the mpy (mils per year) unit (1 mil is equivalent to one thousandth of an inch). To convert corrosion rate (corrosion rate conversion) between the mpy and the equivalent in metric unit mm/yr (millimeter per year):

1 mpy = 0.0254 mm/yr = 25.4 µ/yr

1 mm/yr = 39.37 mpy = 1,000 µ/yr **Eq. 2-8**

To calculate the corrosion rate from uniform metal loss:

mpy = 534 x (W/DAT)

mm/yr = 87.6 x (W/DAT) **Eq. 2-9**

where:

W = weight loss in milligrams
D = metal density in g/cm^3
A = area of sample in cm^2 (for mm/year) or in^2 (for mpy)
T = time of exposure of the metal sample in hours

EPRI report 1025256 provides a literature review of soil-side corrosion rates for buried metallic piping.[11] This study involved a review of existing industry corrosion rate data, judgment regarding its credibility and applicability, and a summary of the results with guidance regarding corrosion rates as a function of degradation type, materials, and the environment.

2.6.1 Electrical Effects on the Rate of Corrosion

Any factor that affects the amount of current flowing in a circuit will affect the rate of corrosion. Ohm's law states that the direct current flowing in a circuit is directly proportional to the potential difference and the total resistance of the circuit. It is formulated as $E = IR$ (or $V = IR$), where E is the potential difference, or voltage, I is the current, and R is the equivalent resistance of the circuit. The following paragraphs provide a summary of factors that affect the rate of corrosion.

2.6.1.1 Potential Difference

The potential difference between the anode and the cathode is an electromotive force and can be measured as voltage. The greater the potential difference, the greater the tendency for corrosion. In accordance with Ohm's law (E=IR), the voltage is directly proportional to the current and

[11] EPRI report 1025256, "A Literature Review of Soil-Side Corrosion Rates for Buried Metallic Piping", September, 2012.

therefore the corrosion in an electrochemical cell. If the voltage is doubled and the electrolyte resistance remains the same, the amount of corrosion will double.

2.6.1.2 Resistivity of the Electrolyte

Soil resistivity is a measure of how easy it is for ions to flow in the soil. The flow of ions is essential in most corrosion reactions. Other factors being equal, corrosion reactions will proceed more easily when the resistance to ionic current flow is lower and proceeds more slowly in soils with higher resistivity. In an electrochemical cell, current is inversely proportional to resistivity (I=E/R). If the electrolyte resistivity is doubled, and all other factors are equal, the amount of corrosion is reduced by one-half.

2.6.1.3 Contact Resistance

The contact resistance of the anode-to-electrolyte and of the cathode-to-electrolyte is a component of the overall corrosion cell resistance and therefore the lower the contact resistance, the greater the corrosion current. As the contact resistance increases, the corrosion cell current will decrease. The decrease in corrosion current is directly related to the sum of the total resistance of the circuit, that is the resistance of the electrolyte plus the contact resistance.

2.6.1.4 Coating of the Structure

The coating on the structure surface normally raises the contact resistance of both the anode and the cathode since most coatings have a high dielectric (non-conductive) property.

2.6.1.5 Polarization of the Structure

The change of potential at the structure/electrolyte interface as a result of electrochemical current flow is known as polarization. Polarization usually results in the formation of a film on the cathode surface. This polarization film consists partly of a thin film of hydrogen. The polarization film and other changes resulting from current flow have beneficial effects at the cathode. The layer of hydrogen acts as a protective layer to corrosion. Other beneficial changes include: transportation of water away from the surface of the cathode (electro-osmosis), a reduction in the ion concentration of the electrolyte, an increase in the contact resistance of the electrode and essentially a reduction in corrosion current to a fraction of its previous value.

2.6.1.6 Current Flow

The amount of current flow in a corrosion cell directly influences the rate of corrosion. The amount of current flow is determined by the activity of the metal as given in Table 2-1. The amount of metal associated with the transfer of a specific amount of electrons is expressed as pounds per ampere-year as given in Table 2-2. Table 2-2 provides a basis for estimating the amount of anode metal that will be dissolved in a given time.

2.6.1.7 Surface Area Ratios

How rapid the anode corrodes is dependent on the relative size of the anode and cathode areas. The same dissimilar metal relationship can result in a very rapid rate of corrosion when the anodic area is very small compared to a large cathodic area. If the anode is much smaller than the cathode, the corrosion current per unit area will be relatively high and the anode will corrode

rapidly. Under this circumstance corrosion is localized and generally becomes more severe for the relatively small anodic area. However, if the area of the anode is large compared to the area of the cathode, corrosion current per unit area will be relatively small and the anode will corrode slowly.

The effect of the surface area ratio can be especially pronounced on coated structures. Small coating defects (such as scratches or voids), commonly referred to as holidays, can result in accelerated corrosion of the metal exposed to the electrolyte. The corrosion current concentrates at the holidays and corrosion is more rapid than it would be on an uncoated structure. Under stray current conditions, this size relationship can be extremely critical. The discharge current density from the pipe under stray current conditions can be very high, resulting in failure of the pipe in an extremely short period of time.

2.6.2 Factors Affecting the Rate of Corrosion

Any factor, which affects the speed of a chemical reaction, will affect the rate of the electrochemical reaction (corrosion). The following is a description and examples of other factors that affect the rate of corrosion.

2.6.2.1 Temperature

Temperature is a complex external variable to the electrochemical corrosion cell. A more active metal is anodic to a more noble metal. Metal at an elevated temperature becomes anodic to the same metal at a lower temperature. Generally, as the temperature increases, corrosion will increase. Although the discharge water of condenser circulating water (CCW) lines will be higher in temperature than the intake water, the temperature rise in the soil environment may be insignificant. Therefore the effect that temperature has on external corrosion of buried nuclear piping may not be a concern.

2.6.2.2 pH of the Electrolyte

The pH of the electrolyte in an electrochemical corrosion cell affects the rate of the corrosion by speeding up or slowing down the chemical reactions at the anode and/or the cathode. The pH of an electrolyte is basically the concentration of hydrogen ions. A pH below 4 increases the corrosion rate of mild steel. At a pH of 3 the corrosion rate of steel will increase substantially. Metals having the capacity to react as either an acid or a base, known as amphoteric metals, also show an increase in the corrosion rate in alkaline environments. Aluminum and lead are examples of amphoteric metals. Figure 2-12 provides the effect that electrolyte pH has on corrosion rate of aluminum and mild steel.

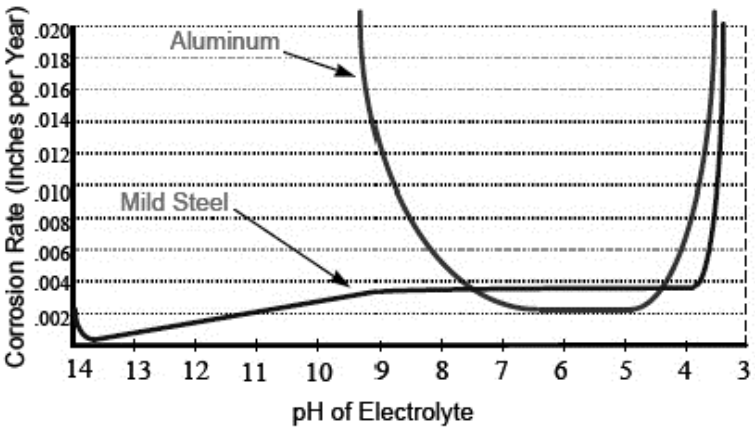


Figure 2-12
Effect of Electrolyte pH on the Rate of Corrosion
(Source: UFC 3-570-06)

2.6.2.3 Ion Concentration

For some metals, ion concentration has an effect on corrosion similar to pH. For example, aluminum corrodes not only by alkalis, but shows pronounced attack by traces of copper ions in aqueous media and is subject to rapid attack by mercury metal, mercury ions, and anhydrous chlorinated solvents. Iron is subject to attack by chlorides, which may increase the corrosion rate in some electrolytes; however, bromide and iodide ions may slow down (inhibit) the rate of corrosion. The effect of concentration of one ion on corrosion is dependent on other environmental variables present in the electrolyte, such as the presence of salts, availability of oxygen, and differences in oxygen solubility, pH, and temperature. The saturation of the electrolyte by high concentrations of free ions around the cathode can inhibit corrosion due to the maximum ion migration rate through the electrolyte environment. Conversely, very low concentrations of free ions in the electrolyte around the cathode could increase the rate of corrosion rate through the establishment of chemical equilibrium.

2.7 Corrosion Prevention

Corrosion can be controlled by using one or a combination of methods. Corrosion is a common phenomenon and affects most materials and material combinations. For buried piping there are three general methods available to limit external corrosion.

2.7.1 Material Selection

The process of selecting materials for construction of piping systems that are exposed to soil is a critical first step in corrosion prevention. Where possible, materials such as stainless steels, plastics, and special alloys should be selected to enhance the life span of a structure. Selecting the metals that are close in potential in the galvanic series reduces the possibility of dissimilar metal corrosion. Alloying may provide better corrosion resistance and for example, type 304 and 316 stainless steels and super austenitic stainless steels (6% molybdenum content) have been used for buried piping at several nuclear power plants and provide substantial resistance to corrosion in soils. However care must be taken when using these materials to avoid anaerobic conditions, electrolytes with high chloride concentration and dissimilar metal corrosion.

Depending on the environment, stainless steel, titanium and concrete pipes may not need cathodic protection. In fact GALL Report Revision 2 AMP XI.M41 does not require cathodic protection as a preventive action when using these materials. However since these piping systems are connected to other piping systems which may have cathodic protection, the protective current from the CP systems may be inadvertently received on these structures.

2.7.2 Coatings

Coatings form the first line of defense against corrosion and are a widely used method for corrosion protection. A coatings database for buried nuclear piping can be found in EPRI Product 1024604.[12] The selection of a coating system for a given buried pipe should be based on laboratory, *in situ* field testing and operating experience (OE). A properly selected and applied coating system will provide an effective barrier to corrosion by isolating the structure from its installed environment/electrolyte. Although coatings by themselves may not be the perfect answer to corrosion control, a well coated pipeline should provide more than 99% of the corrosion protection on the pipeline surface. When used in conjunction with an effective cathodic protection system, total protection can be provided to the buried pipe.

Cathodic protection is a widely used and effective method of corrosion control. In theory it is defined as the reduction or elimination of corrosion by making the metal a cathode via an impressed direct current (DC), or by connecting it to a sacrificial or galvanic anode. Cathodic areas in an electrochemical cell do not corrode. By definition, if all the anode sites were forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated. On new structures, CP can help prevent corrosion from evolving and for existing structures it can slow the growth of existing corrosion.

[12] EPRI Product 1024604, *Coatings Option Database*, Version 2.0, July 2012.

3
CATHODIC PROTECTION SYSTEMS

Corrosion can be prevented by coupling a metal with a more active metal when both are immersed in the same electrolyte and connected with an external metallic path (galvanic anode) or by having a source of direct current to overcome the electrochemical cell responsible for corrosion (impressed current). Direct current is forced onto all surfaces of the pipeline, resulting in a shift of potential in the active (negative) direction and consequently a reduction in the corrosion rate of the metal surface in contact with the electrolyte. When the amount of current flowing is adjusted properly, it will overpower the corrosion current discharging from the anodic areas on the pipeline and there will be a net current flow onto the pipe surface at these points. The entire surface will become the cathode; hence the term "cathodic protection".

Cathodic protection, when properly designed, installed and maintained, can control corrosion of buried piping effectively. Criteria provided by NACE can be used for determining whether adequate corrosion control is being achieved. Many articles have been published demonstrating the effectiveness of CP in preventing the development of leaks on pipelines. However at nuclear power plants it must be understood that space limitations may preclude installation of anodes in certain areas. For instance the large diameter pipes beneath a turbine building slab will receive limited protection from anodes installed in the soil around the periphery of the building. Furthermore, shielding effects from other buried structures such as shoring, building foundations, and other piping may limit distribution of the protective current. Thus, it is possible that certain sections of piping may have marginal protection or no protection at all. Nevertheless, the reduction in corrosion rate can be significant, even when a reduced level of cathodic polarization is realized on the pipe surface.

There are two types of CP systems: the impressed current system (which is considered an active CP system) and the galvanic or sacrificial anode system (which is considered a passive CP system). Because of the significant current requirement and the required service life, the impressed current method is almost always used for cathodic protection of buried piping at nuclear power plants. Galvanic anode systems require electrical isolation of the piping network for effective operation and therefore have limited use at a nuclear plant, unless insulating devices can be installed. These techniques are discussed briefly below. More detailed information can be found in *Peabody's Control of Pipeline Corrosion*.



Key Technical Point

Because of the significant current requirement and the required service life, the impressed current method is almost always used for cathodic protection of buried piping at nuclear power plants.

3.1 Impressed Current System

3.1.1 General Description

The impressed current system is designed to deliver a relatively large amount of current from a limited number of anodes. An impressed current system uses an external DC power supply, such as a rectifier, to force an external direct current from the anode material through the soil to the structure being protected. With this type of system, the anodes are installed in the electrolyte and connected to the positive (+) terminal of the DC power supply and the structure being protected is connected to the negative (-) terminal of the power supply. The current is impressed onto the pipeline surface from the anode groundbed.

The most common power source for impressed current systems is the rectifier. This device converts alternating current (AC) power to direct current (DC) power. Rectifiers are usually provided with the means of varying the DC output voltage, in small increments, over a reasonably large range. Although the maximum output voltage may be less than 10 Volts or close to 100 Volts, most rectifiers for buried piping systems operate in the 10 to 50 Volts range and can be obtained with maximum current ratings from less than 10 Amperes to several 100 Amperes. AC power requirements for rectifiers are typically not excessive. For example, using 440 VAC, 3 phase power, a rectifier operating at a DC output of 50 Volts / 50 Amps would draw only 4.8 Amperes of alternating current.

The external current is impressed into the soil using inert anodes which form an anode groundbed. Materials such as graphite, high silicon cast iron and mixed metal oxide (MMO) coated titanium are commonly used as impressed current anodes in soil because they have a very low consumption rate. Individual anodes may be bare or pre-packaged in spiral constructed steel canisters. To provide extended life and lower the effective resistance-to-earth, the anodes are encapsulated in a coke breeze backfill. Anode beds may be surface anode beds, deep anode or semi-deep anode groundbeds, distributed anodes or linear anode systems. Anodes that are installed vertically in a hole are termed anode wells. Typically anode cables will terminate in a nearby junction box. The anode junction boxes may contain shunts to measure the individual anode currents. Anode cables may also be spliced to a header cable underground using waterproof splice kits. However, this method does not allow measurement of individual anode currents. Furthermore it is more prone to failure as the splice kits may fail resulting in a breakage of the header cable.



Key O&M Cost Point

Materials such as graphite, high silicon cast iron, platinum, or mixed metal oxide (MMO) are commonly used as impressed current anodes in soil because they have a very low consumption rate.

A typical impressed system may consist of the following components:

- Inert anodes
- Carbonaceous backfill around the anodes
- DC power source (rectifier)

- Inter connecting cables
- Structure connection
- Anode junction box

Figure 3-1 provides a schematic of an impressed current CP system.

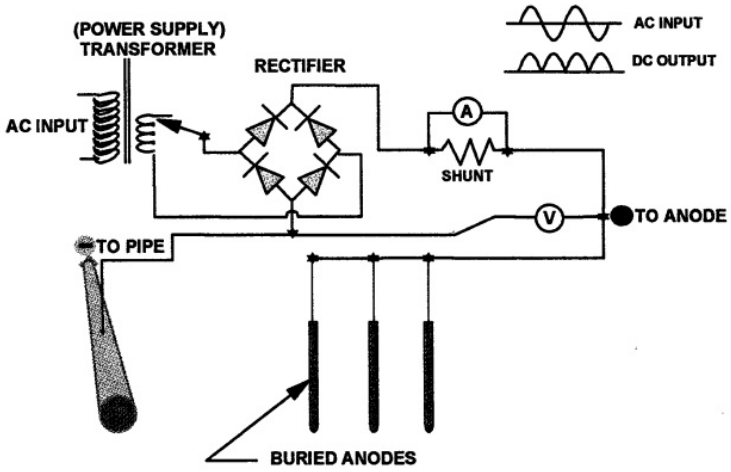


Figure 3-1
Schematic of an Impressed Current CP System

3.1.2 Impressed Current Anodes

The following sections provide an overview of impressed current anodes commonly used for cathodic protection of buried structures. Cables for impressed current anodes consist of insulated copper conductors that are sealed at the connection point to prevent moisture ingress and hence premature failure. Details regarding the size and rating of these anodes is available from various CP material suppliers.

3.1.2.1. Graphite

Graphite has been widely used for many years as an anode material in soil. Usually they are rated at a current output of up to 1.0 Amp/ft^2 when backfilled with carbonaceous backfill. A 3-in. diameter x 60-in. long anode would have a maximum output of approximately 4.0 Amperes. Graphite anodes are consumed at no more than 2 lbs/amp/year when discharging current into an electrolyte. When used with carbonaceous backfill with direct electrical contact, most of the material consumed is the backfill material rather than the anode itself. Graphite anodes may be prepackaged with coke in metallic canisters or bare, with coke breeze added to encapsulate the anodes in the field. Graphite anodes are brittle and must be handled with care.

3.1.2.2 High Silicon Cast Iron

High silicon cast iron anodes normally contain between 14 and 15% silicon and lesser quantities of other alloying elements. When encapsulated in carbonaceous backfill typical anode current densities are reported to be 0.5-1.0 amps/ft^2 and nominal consumption rates are generally between 0.1 and 0.25 lbs/amp/year. Similar to graphite, the material is somewhat brittle and must be handled with care. They are available in various sizes and shapes. A common size used in

impressed current ground beds is 2-in. diameter by 60-in. length. They are used commonly with carbonaceous backfill, which absorbs most of the consumption resulting from the current discharge.

3.1.2.3 Mixed Metal Oxide (MMO)

Mixed metal oxide (MMO) anodes consist of a precious metal oxide (catalyst) that is sintered to a Grade 1 Titanium substrate. For soil applications MMO anodes are provided in various configurations including rod, wire and tubes. To provide the longest anode life the catalytic coating should be Iridium Oxide (IrO_2) and the coating thickness should be type XXL. Due to the extremely low consumption rates and dimensional stability of the MMO anode, the electrical resistance of the anode remains relatively constant with time. These anodes are relatively inert and can operate in a variety of environments. MMO anodes can be operated at high current densities with very low consumption rate (measured in terms of milligrams per amp-year). Since the substrate is titanium, MMO anodes are not as brittle as graphite or cast iron anodes. However care must be taken during transport and installation to avoid damage to the catalytic coating. Since MMO anodes are relatively light weight compared to graphite and cast iron anodes, handling, transportation and installation are easier. A common size for a center connected tubular MMO anode is 1-in. diameter by 40-in. in length.

3.1.3 Carbonaceous Backfill

The term “carbonaceous backfill” describes the backfill that is used to encapsulate impressed current anodes. Carbonaceous backfill is normally supplied as metallurgical coke breeze or calcined petroleum coke breeze. Carbonaceous backfill serves two purposes when surrounding impressed current anodes:

- To increase the size of the anode to obtain lower resistance to earth, and
- To bear most of the consumption resulting from current discharge.

The latter function requires good electrical contact between the anode and backfill particles. To accomplish this, the backfill must be tamped solidly around the core. Occasionally, subsurface soil conditions may not allow adequate contact pressure, or may relax with time, so that much of the current will discharge directly from the anode to the electrolyte. This tends to reduce anode life. Consumption rate of the backfill should not exceed two pounds per ampere per year. Petroleum grade coke provides the best overall performance is typically used in deep and semi-deep anode groundbeds. Suppliers can provide specific information on the coke breeze material being supplied. Coke breeze should be procured by specification. Size and resistivity are important.

3.1.4 Rectifiers

The proper selection of the DC power supply for cathodic protection is important to ensure a relatively long life and maintenance free impressed current system. Various types of rectifiers are available for cathodic protection including: manual voltage control, constant current and potential controlled rectifiers. Manual voltage control rectifiers require adjustment of the transformer taps to change the output. This type of rectifier is considered a conventional rectifier and is commonly used in the pipeline industry. When the electrolyte resistivity changes due to changing moisture content, a constant current controlled rectifier may be required to maintain the

correct current applied to the structure being protected. Under certain circumstances, potential controlled rectifiers are used to maintain a constant potential on the pipeline, which changes to match the pipeline current requirements. These types of rectifiers are best suited for structures that are subject to dynamic stray current activity from DC transit systems or mining operations, and require installation of a permanent reference electrode at the point where the pipe-to-soil potential is being monitored / maintained. A constant current rectifier maintains a constant direct current output as the resistance of the electrolyte changes. Potential controlled rectifiers and constant current rectifiers are termed automatic rectifiers. These differ from manual voltage control rectifiers in that electronic controllers (control cards) are required for operation.

Manufactures produce rectifier units with a wide range of DC output and AC input ratings. Sufficient spare capacity should be provided in the rectifier output voltage to account for seasonal changes in the anode bed resistance. Rectifying elements typically consist of silicon diodes, with upgraded lightning protection. DC output control should be provided by manual tap-switch adjustment. Various options are available for mounting the rectifier enclosure including pole mount, floor mount and wall mount. Stainless steel cabinets and/or oil immersed enclosures should be considered where a corrosive atmosphere exists.

Interruption of the rectifier DC output is required for measurement of the IR drop free instant-off (polarized) potential. Therefore synchronization of the interruption cycle of all the CP rectifiers at a plant site is necessary when multiple power supplies are used. This can be accomplished by having an external connection for a portable current interrupter or by having a global positioning system (GPS) synchronized current interrupter installed in each rectifier. When an integral current interrupter is installed in the rectifier, a manual by-pass switch should be built into the rectifier to take the interrupter out of the circuit when not in use. Figure 3-2 provides a view of two air-cooled rectifier units at a nuclear power plant.



Figure 3-2
Rectifier and Anode Junction Box Installation
(Source: PSEG Nuclear, LLC)

Manufacturer's instructions as well as station operating procedures should be followed when handling rectifier equipment. Safety features that may be considered when specifying a rectifier include:

- Tap switch adjustment (allows adjustment of rectifier without using link bars)
- Dead front fuse holders (allows safe removal and insertion of fuses)
- GFI receptacle complete with over load breaker protection (allows safe power access for 120 VAC)
- "Touch Safe" Lexan barrier to cover all exposed DC components located on the front panel of the rectifier, and
- Interruption Ports / Terminals (allow for easy connection of portable current interrupters without the need to disconnect any of the rectifier wiring)



Key Human Performance Point

Manufacturer's instructions as well as station operating procedures should be followed when handling rectifier equipment. Safety related features should be considered when specifying a rectifier.

3.1.5 Remote Monitoring

Remote monitoring of the rectifier DC output may be considered if communication features are deemed suitable by plant security. Remote monitoring systems enable remote data gathering and minimize the need for maintenance personnel to read the rectifier output, which is typically performed on a bi-monthly basis. Therefore remote monitoring will typically reduce the preventive maintenance task associated with cathodic protection. Remote monitoring can also facilitate data gathering and trending of rectifier data. Communication can be provided by digital cellular, satellite networks or hard wire. Two-way communication may also be provided with field upgradeable GPS synchronized current interrupters. Alarm status may be provided to alert operators that the rectifier is operating outside a specific target range. Notifications of equipment status may be provided via email, voice and/or text.

3.1.6 Interconnecting Cables

All underground anode cables, which are a part of an impressed current groundbed, are at a positive potential with respect to earth. Current carrying positive conductors must be insulated. If the cable is not perfectly insulated, the exposed copper will discharge current into the electrolyte and the cable will sever after the system is energized. Thus, quality insulation must be used on all anode leads and ground bed header cables.

Anode cable insulation should be suitable for direct burial. Wire with a high molecular weight polyethylene (HMWPE) insulation is widely used for impressed current anode groundbeds. If salts or other contaminants are present in the soil, corrosive gases such as chlorine may be released at the anode surface and therefore an additional protective inner jacket of HALAR® may be necessary to insulate the anode cable. Cable should be inspected carefully during

installation to be absolutely sure that there are no scars or cuts which later could present problems. Ideally splices in the underground cables should be minimized. Any damage in the cable insulation must be encapsulated using a heat shrink sleeve or waterproof splice kit.

The rectifier DC negative cables of an impressed current system are not as susceptible to breakage as the buried anode cables, since the exposed copper at a cable insulation flaw would be protected from the cathodic protection current. Nevertheless care should be exercised when installing the negative cables in the ground.

Catalog information for anode cable suitable for groundbed construction is available through various CP material suppliers. Selecting cable size has both a practical and an economic aspect. From the practical standpoint, the cable should be large enough to carry the intended current (see National Electric Code[13] for tables of current rating) and to withstand mechanical stresses encountered during groundbed construction. Cable sizes smaller than No. 8 AWG for impressed current anode cable are not adequate. Anodes should never be installed by holding the cable as this could result in stress on the anode-to-cable connection. Similarly, cable sizes that are unusually large may cause handling and connection problems during construction. From an economic standpoint, cable sizes should be selected based on a comparison of cable cost with current carrying capacity.

3.1.7 Structure Connections

When excavation of the pipe to be protected is difficult (due to depth or congestion), system negative connections to the structure can be made to above ground piping or to station ground. Continuity checks should be made to ensure the proposed ground connection is electrically continuous with the pipeline being protected. Ideally cable connections should be made using the thermite welding method, pin brazing method or by welding a steel tab (using approved methods) to the structure for connection of the cable. Alternate connections may be used such as clamps to allow compliance with plant procedures. All structure negative connections should be coated with epoxy or other approved material, to prevent moisture ingress. Figure 3-3 shows a typical structure connection detail for a system negative cable or test lead cable at a nuclear power plant.

[13] NFPA 70: National Electric Code®, (NEC®), 2011 Edition.

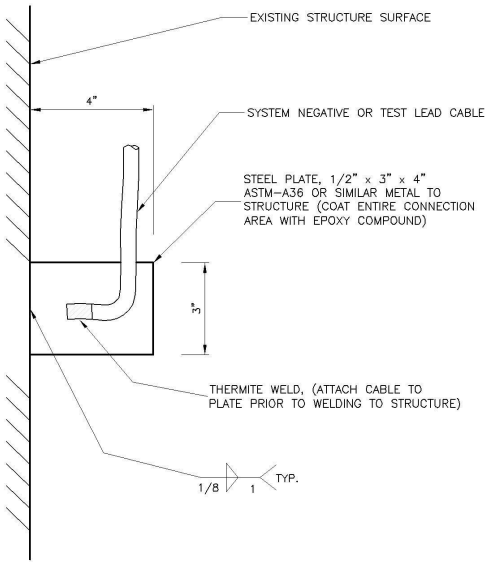


Figure 3-3
Structure Connection Detail

3.1.8 Anode Junction Boxes

The anode cables are normally brought into a junction box where the cables are connected to a common buss bar. Current measuring shunts may be included to allow measurement of the individual anode currents. Junction boxes may be constructed of stainless steel or fiberglass reinforced plastic (FRP). Figure 3-4 shows a view of the internal cabling inside a typical junction box.

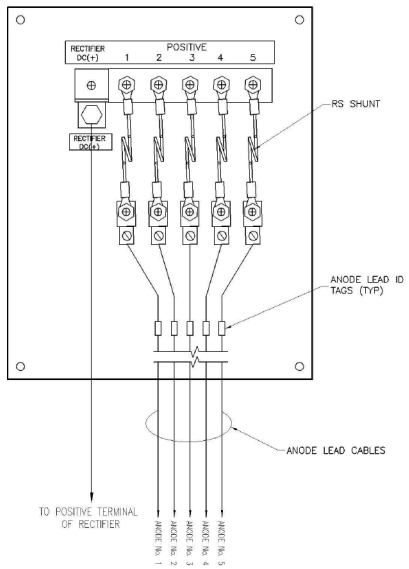


Figure 3-4
Junction Box Internal Cabling

3.1.9 Anode Groundbeds

The flow of cathodic protection current from an external source through the electrolyte (soil) to the pipeline will be accompanied by a potential difference between the earth and the pipeline, with the earth being positive (+) and the pipeline negative (-). This potential is used in certain CP criteria to demonstrate the degree of cathodic protection being afforded the pipeline. Developing the desired structure-to-soil potential can be accomplished in two ways:

- By making the piping negative (-) with respect to remote earth, or
- By making the earth positive (+) with respect to the piping in localized areas

The method of making the piping negative with respect to remote earth is accomplished by using anodes installed in wholly or partially remote earth. The method of making the earth positive with respect to the pipe is accomplished by using anodes that are installed in close proximity to the pipe. Remotely placed anodes, such as surface anode beds and deep anode beds, may not provide sufficient current to overcome the galvanic coupling at building entrances and in congested areas where the surface area of copper grounding is significant. In these areas the installation of supplemental anodes may be required to increase the level of protection to the buried piping, so that adequate protection is provided.

The number of anodes and spacing between the anodes is based on the total current demand for cathodic protection, the current capacity of the anodes and the desired anode-to-earth resistance. When designing an anode system for buried piping, the effective soil resistivity in which the anodes are to be placed should be known, so that the anode-to-earth resistance can be calculated. Ideally the anode-to-earth resistance should be less than two (2) ohms, to allow even distribution of the current at a reasonably low impressed voltage. This target resistance however may not be obtainable, especially in higher resistivity soils. Installation of the anodes below the water table will typically provide the lowest possible resistance. The following sections describe the various types of anode groundbeds for impressed current systems.

3.1.9.1 Surface Anode Beds

Surface anode beds, as the name implies, are shallow anode beds that are buried at a significant distance from the piping to be protected. Surface anode beds may consist of horizontally or vertically installed anodes that are installed laterally away from the structure. Shielding effects should be considered when designing surface anode beds and ideally no buried structures should be positioned between the surface anode bed and the structure being protected. The anodes in surface beds may consist of pre-packaged canister anodes or bare anodes that are backfilled with coke breeze. Because the number of anodes for surface anode beds can be significant, space limitations at the plant may limit the use of this method. Figure 3-5 provides a schematic view of cathodic protection to a buried pipeline from a surface anode bed.

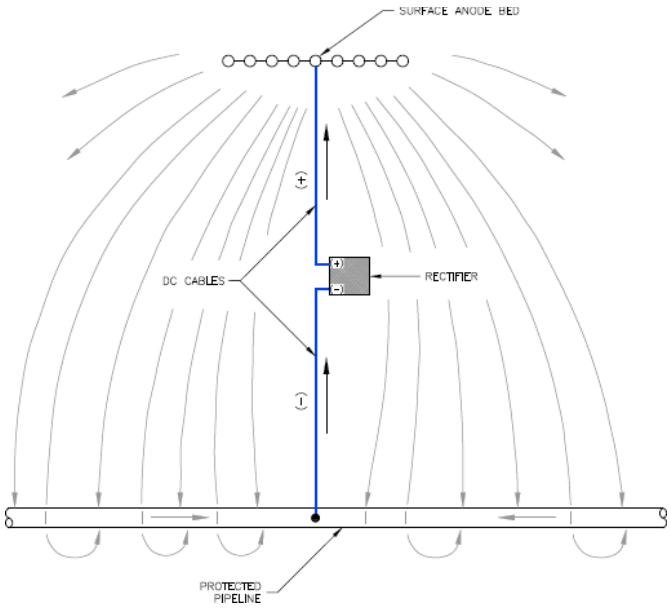


Figure 3-5
Schematic of a Surface Anode Bed

3.1.9.2 Deep Anode Beds

Deep anode systems are anode systems that extend down vertically from the surface in a drilled hole. The depth of the installation may be several 100 ft (30 m) or more depending on the depth of bedrock. NACE Standard Practice SP0572-2007 "Design, Installation, Operation and Maintenance of Impressed Current Deep Anode Beds" provides guidance regarding these systems. The main benefit of using deep anode beds is that they can be located in congested areas, where shallow beds may pose problems with respect to excavation and trenching and possible shielding of the intended piping by other buried structures. The deep anode systems are suitable where bedrock formations are relatively deep and surface soil resistivities are high. However, the deep earth formation must be sufficiently low in resistivity to permit construction of the deep anode system, so it will radiate the current to the structure at a reasonable impressed voltage. An estimate of the deep formation resistivity may be obtained from soil boring logs in geotechnical reports or from site resistivity measurements. However, historical information (resistance trending data) from existing nearby deep anode beds is most valuable.

The designer of a deep anode system should reference the groundwater protection plan, so as to avoid potential pollution and cross contamination of subsurface aquifers. Non-porous clay seals are available from cathodic protection system suppliers, which prevent contamination of underground aquifers from surface fluids.

Key Technical Point

The designer of a deep anode system should reference the groundwater protection plan, so as to avoid potential pollution and cross contamination of subsurface aquifers.

Deep anode beds may also be considered semi-deep [i.e., <100 ft (30 m)] when bedrock formations are closer to the surface and the total depth of the anode column is relatively shallow. To eliminate anode current leakage, the upper section of the anodes should be backfilled with a non-conductive material and a vault or cover installed over the wellhead. Calcined petroleum coke backfill is most often used as a backfill for deep anode systems and anode centralizers are used to position the anodes in the center of the coke breeze. Anode vent systems are typically used with deep anode beds to release gases generated at the anode interface and as a facility for the addition of water if needed. Gases may be corrosive and can increase the effective resistance of the groundbed. In some situations a bentonite seal may be necessary to prevent surface fluids from contaminating the underground aquifer. The top of the surface casing should be sealed with a cap to prevent infiltration of contaminates into the anode well. Local restrictions may influence the decision to use certain deep anode configurations, and communication with local authorities is always advisable. When contemplating the installation of a deep anode system in a nuclear power plant the space required for the drilling rig, mud circulation system, water supply, drilling mud, cuttings containment system and disposal need to be considered. Figure 3-6 provides a side view of a deep anode system for buried piping.

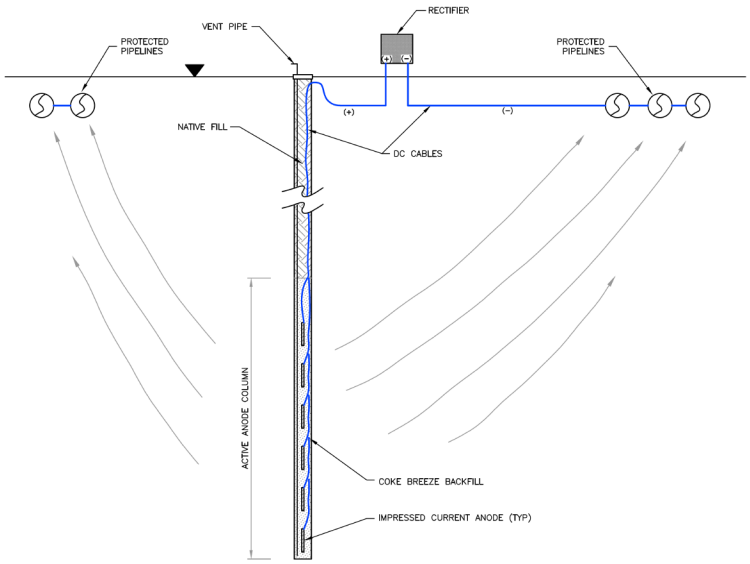


Figure 3-6
View of a Deep Anode System

3.1.9.3 Distributed Anode Beds

Distributed anode beds consist of closely coupled anodes that are installed in close proximity to the pipe. Distributed anode systems are best suited for plants where bedrock formations are relatively shallow, which prevent the use of deep anode systems. The anodes may consist of pre-packaged canister anodes or bare anodes that are installed with coke breeze backfill. For existing plants the anodes are placed vertically in the soil along the pipeline to be protected. Dry or wet vacuum excavation methods may be used to minimize damage to buried structures. If soil conditions permit, two or more anodes can be installed vertically in a shallow hole. If possible, the anodes should be installed in soil below the water table to provide the lowest possible anode-to-earth resistance. Installation of anodes in gravel is not an acceptable practice, as the gravel

will tend to increase the anode-to-earth resistance. Individual anode lead cables should terminate in a junction box, so as to avoid splicing of the cable. Installation of direct buried cable can be expensive and disruptive and existing cable ducts should be used wherever possible.

The closely coupled method is based on the premise that the current per unit area of earth (current density) flowing away from the anode is highest close to the anode and decreases with distance away from the anode. Protective potentials that may be realized on a buried pipe from a distributed anode are shown in Figure 3-7. The principle of protection relies on the fact that the length of pipe receiving protection by a single close anode depends on changing the potential of the earth around the pipeline rather than changing the potential of the pipeline with respect to earth. The amount of earth potential change (and hence the length of pipe that can be protected) is a function of the voltage impressed on the anode, rather than the amount of current discharged from the anode. For nuclear power plants the distributed anode systems will typically provide the most uniform current distribution to the pipe. They are ideal for congested areas where electrical shielding precludes the effective use of remote anode beds. An additional benefit of this type of anode system is that in areas where the potential of the buried pipe is depressed from the dissimilar metal coupling to copper grounding, stainless steel and/or reinforcing steel in concrete, the distributed anode method may afford the best degree of protection.

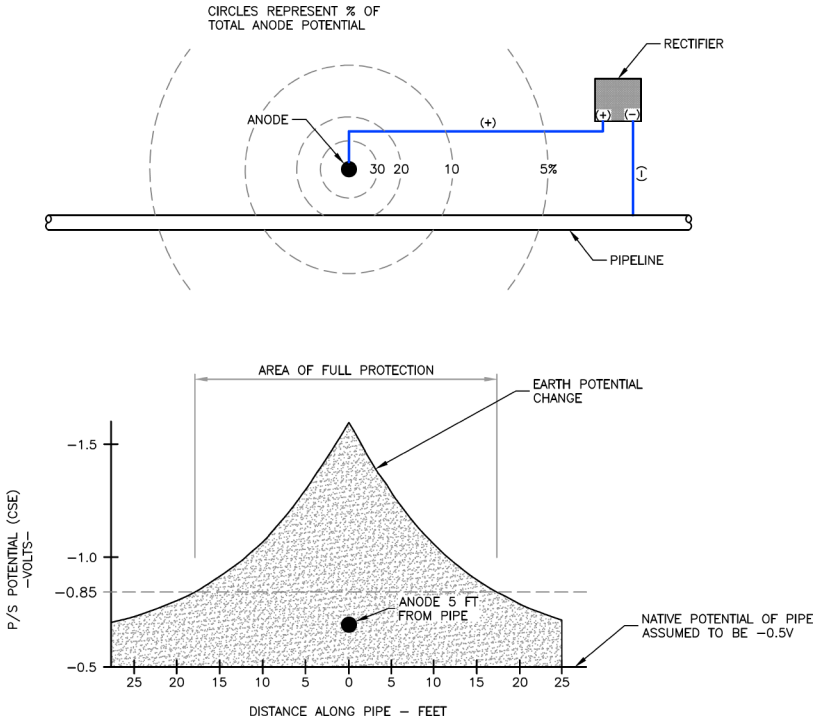


Figure 3-7
Example of Protective Potentials Impressed on a Buried Pipe from a Distributed Anode

3.1.9.4 Linear Anode Systems

Linear anodes consist of prefabricated flexible long-line anode assemblies that are best suited for new construction, as the anode assembly and cabling can be installed in the same trench as the pipe. For existing nuclear power plants, linear anodes may be installed parallel to the buried pipes using the horizontal directional drilling (HDD) method providing that there is sufficient space for equipment set-up at the entry and exit points for the auger, and the location of all

buried utilities and infrastructure are known. Linear anode systems will typically provide more uniform current distribution to the piping, lower anode-to-earth resistance and lower current density for cathodic protection compared to other systems. As shown in Figure 3-8, linear anode assemblies are typically supplied with a No. 8 AWG copper conductor with high molecular weight polyethylene (HMWPE) insulation (central bus cable) that is spliced to a continuous copper-cored mixed metal oxide (MMO) anode wire. The wire and cable are prepackaged in calcined petroleum coke breeze using an acid resistance fabric jacket and protective monofilament braid. A second HMWPE insulated copper conductor (loop cable) is added in the field to provide redundancy and to lower voltage drop. The anode assembly diameter is typically 1.5 in (37 mm) nominal, therefore a 2 in (50 mm) bore hole for HDD is suitable. If the location of buried structures is not known or if safety related pipe is in close proximity to the proposed drill hole, then the use of linear anode systems for cathodic protection of existing buried pipe may not be an option.

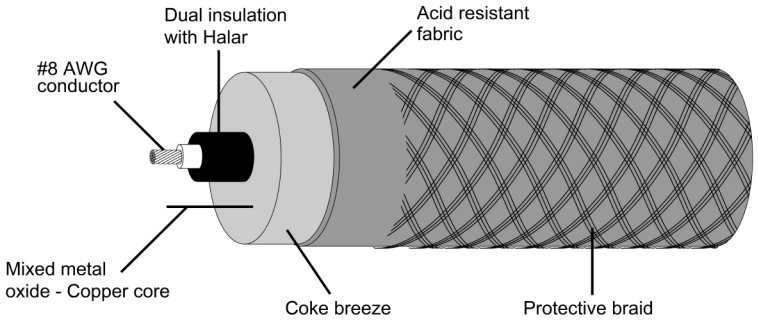


Figure 3-8
Linear Anode Assembly
(Source: Berry Plastics CPG)

3.1.9.5 Water Consumption and Replacement

Anodic reactions at the anode-soil interface may result in the consumption of water through electrolysis of the water and the production of oxygen gas. The rate of electrochemical change and consumption of water at the anode/soil interface is controlled by the rate of electron transfer. Although the actual quantity of water consumption from electrolysis is relatively small, the movement of water away from anode interface may also be depleted by electro-osmosis. Through this process, water is driven away from the anode surface by the current discharged, which in turn is replenished by the natural hydraulic gradients in the earth providing some level of equilibrium. The worst case involves fine-grained, low permeability soils, where water movement towards the discharge surface is relatively slow resulting in a depletion of the water at the interface and an increase in the anode-to-earth resistance. If the condition is such that insufficient moisture is present, the resistance of the anode bed may increase to the point where an adequate level of current cannot be delivered from the rectifier. This process is sometimes referred to as anode “dry-out” and is more prevalent in drier, more arid climates. If this is the case, an artificial water supply must be provided to the anode groundbed, or the current discharged from the rectifier must be reduced to a point where equilibrium is established. The latter, however may result in loss of protection to the buried piping and additional anodes may be required to lower the anode groundbed resistance. If a supplemental water supply is required, potable water should be introduced through the venting system (if present).

3.2 Galvanic Anode System

3.2.1 General Description

The galvanic anode system of protection is based on dissimilar metal corrosion and makes use of metals which have a higher energy level or potential with respect to the structure being protected. For buried piping applications, the galvanic anodes are generally used where relatively small amounts of current are required and areas where the soil resistivity is low enough to permit obtaining the desired current with a reasonable number of anodes. These types of systems have limited application at nuclear power plants because of the relatively small amount of current that is produced and the fact that they typically require the piping to be electrically isolated (fitted with insulating devices) to contain the protective current.



Key Technical Point

Because of the relatively small amount of current that is produced and the fact that they typically require the piping to be electrically isolated (fitted with insulating devices) to contain the protective current, galvanic anode systems have limited application at nuclear power plants.

Galvanic anodes for cathodic protection consist of magnesium, zinc or aluminum. The two galvanic anodes that are commonly used for buried pipelines are magnesium and zinc. Aluminum has a theoretical energy consumption (in terms of ampere-hours per pound) that exceeds magnesium and zinc; however it is primarily used for marine applications because of problems with passivation effects when used in soil environments.

With the galvanic type of protection, the anode material is consumed or sacrificed in the process. For buried structures, it is common practice to design the galvanic anode system for a 10 to 15 year service life. After the anodes have been consumed and the protective levels on the structure have decreased, the anodes will require replacement. Galvanic anodes will also suffer from self-corrosion. The ratio of metal expended in producing useful CP current to the total metal is termed anode efficiency. Magnesium has a lower efficiency and will tend to self-consume more quickly compared to zinc. Anode life is primarily a function of the anode weight, efficiency and the current output.

Galvanic anodes may be directly bonded to the pipe or installed with lead wires or header cables that are connected to the structure (pipe) through a test station. A test station with test lead wires that are connected directly to the pipe is the preferred method of installing galvanic anodes because it allows the operator to disconnect the anodes for testing and trouble shooting. A current measuring shunt may also be installed in the test station to allow measurement of the anode current. Galvanic anodes may also be installed in open excavations and can be used for "hot spot" protection. The components of a galvanic anode system may include:

- Galvanic anode
- Interconnecting cable
- Test station

The main benefit of galvanic anodes is that they are relatively inexpensive; less complicated than the impressed current method and require minimal maintenance after they are installed. Figure 3-9 provides a basic schematic of a galvanic anode system.

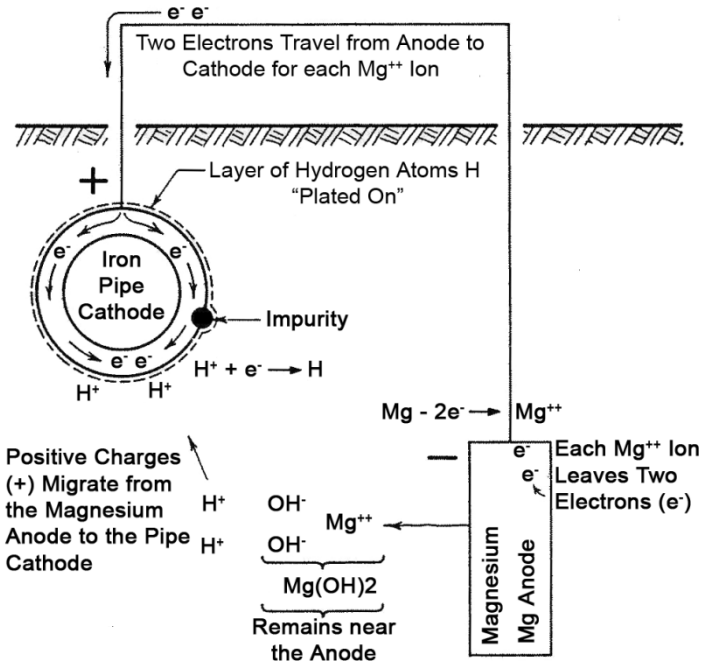


Figure 3-9
Galvanic Anode System
(Source: Cathodic Protection, Applegate, Lindsay, McGraw-Hill, 1960)

3.2.2 Limitations of Galvanic Anodes

Under normal circumstances, the current available from galvanic anodes is limited. For this reason, CP by galvanic anodes normally is used where the current required for protection is relatively small (typically less than 1 Ampere). Similarly the driving voltage between the pipe steel and galvanic anode is limited. Therefore, the contact resistance (resistance-to-earth) must be low enough for the anodes to discharge a useful amount of current. For normal applications galvanic anodes are used in low resistivity soils (typically less than 10,000 ohm-cm). Normally piping systems that are protected with galvanic anodes systems are well coated and fitted with insulating devices, otherwise the current will tend to flow to other structures. Insulating devices include dielectric unions, insulating flange kits and insulating spools that are designed to electrically isolate the protected piping from station ground. Under these conditions the current demand for CP will be relatively low and the galvanic anode system can be expected to protect a substantial length of pipe. However, if the insulating devices are shorted or are not incorporated into the piping system design, the galvanic anodes will consume rapidly and protection levels will be compromised.

There are also instances where galvanic anodes are placed at specific points on a pipeline (often termed hot spots) and may be expected to protect only a few feet of pipe, especially where the line is bare or not electrically isolated. The Figure 3-10 shows a typical galvanic anode installation on a buried pipeline where the anode is connected directly to the pipe.

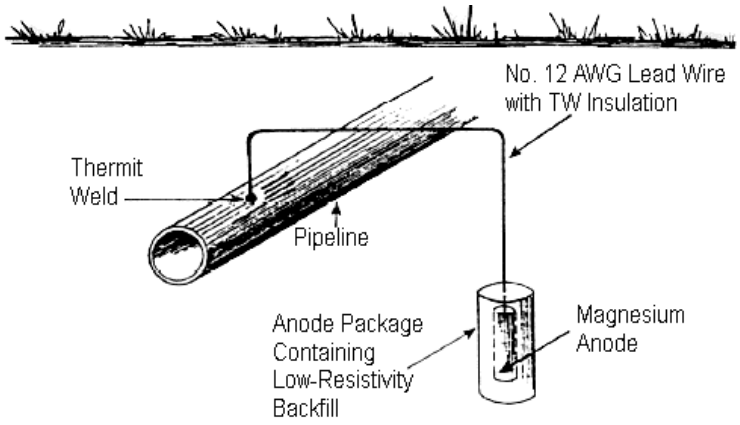


Figure 3-10
Typical Galvanic Anode System Installation
(Source: US Army Center for Public Works Technical Bulletin 420-49-29)

Since the buried piping at nuclear power plants is connected to the copper grounding grid, much of the current will flow to other structures and the current requirement for CP will be relatively large. Unless the anodes are used for "hot spot" protection, the galvanic anode method of protection should only be considered for buried pipes that are coated and electrically isolated.

Key Technical Point

Unless the anodes are used for "hot spot" protection, the galvanic anode method of protection should only be considered for buried pipes that are coated and electrically isolated.

3.2.3 Characteristics of Magnesium and Zinc Anodes

Magnesium is the most widely used material for galvanic anodes. Typical characteristics are given in Table 3-1. The theoretical consumption of magnesium is 8.7 lbs/amp/year. Current efficiency for magnesium is reported to be 50%; therefore the material will tend to self-corrode more readily. Alloys are available in standard potential (H-1 Alloy) and high potential composition. For soil applications the high potential (high purity) alloy is most commonly used because of the higher open circuit potential that is realized (-1.7 to -1.77 V CSE). Magnesium anodes are available in different shapes and weights. Both cast anodes and extruded ribbon forms are available. Cast magnesium anodes are typically supplied in pre-packaged bags with a chemical backfill material. The backfill and anode are contained in a cloth sack. The assembly is usually provided with a paper shipping bag which must be removed before installation. Most anodes are supplied with a 10-ft length of #12 solid TW lead unless otherwise specified. Magnesium anodes are suitable for structures buried in soils with resistivities that generally exceed 2,000 ohm-cm. For soil applications the 17-lb pre-packaged high potential magnesium is most commonly used.

Table 3-1
Characteristics of Magnesium Anodes
(Source: Peabody's Control of Pipeline Corrosion, 2nd Edition, NACE International)

Specific Gravity	1.94
Pounds per Cubic Foot	121
Theoretical Amp Hours per Pound	1,000
Theoretical Pounds per Amp per Year	8.7
Current Efficiency %	50
Actual Amp Hours per Pound	500
Actual Amp Hours per Year	17.4
Solution Potential – Volts CSE (Standard H-1 Alloy)	-1.50 to -1.55
Solution Potential – Volts CSE (High Potential Alloy)	-1.75 to -1.77
Driving Potential Polarized to -0.90 V CSE (Standard H-1 Alloy)	0.55
Driving Potential Polarized to -0.90 V CSE (High Potential Alloy)	0.80

Typical characteristics for zinc anodes are given in Table 3-2. The theoretical consumption of zinc is 23.5 lbs/amp/year. Current efficiency for zinc is reported to be 90% and therefore zinc will not self-consume as readily as magnesium. Zinc alloys are manufactured using 99.99% pure high-grade zinc. These anodes will provide a nominal open circuit potential of -1.1 Volts to a copper-copper sulfate reference electrode (CSE). Zinc anodes are available in different shapes and weights. Both cast anodes and extruded ribbon forms are available. Cast zinc anodes are typically supplied in pre-packaged bags with a chemical backfill material. The backfill and anode are contained in a cloth sack. The assembly is usually provided with a paper shipping bag which must be removed before installation. Most anodes are supplied with a 10-ft length of #12 solid TW lead unless otherwise specified. Because of the passivating films that can form the surface of the anode, zinc anodes are suitable for structures in soil where the resistivity is less than 2,000 ohm-cm. Therefore their use in soil applications is restricted.

Table 3-2
Characteristics of Zinc Anodes
(Source: Peabody's Control of Pipeline Corrosion, 2nd Edition, NACE International)

Specific Gravity	17
Pounds per Cubic Foot	440
Theoretical Amp Hours per Pound	372
Theoretical Pounds per Amp per Year	23.5
Current Efficiency %	90
Actual Amp Hours per Pound	335
Actual Pounds per Amp per Year	26
Solution Potential – Volts CSE	-1.1
Driving Potential to Pipeline (polarized to -0.90 V CSE)	0.2

3.2.4 Galvanic Anode Backfill

For reliable operation in soil, both magnesium and zinc anodes use a chemical backfill to surround the anode. The backfill serves as a uniform material of known composition which reduces localized corrosion of the anode. By isolating the anode material from the soil, the backfill greatly improves performance and efficiency of the anode. Standard backfill composition for magnesium anodes consists of 75% gypsum, 20% bentonite and 5% sodium sulfate. Backfills help in absorbing soil moisture to keep the environment immediately surrounding the anode moist. The anode backfill is low in resistivity and when anodes are installed in soils with higher resistivity, the backfill columns serves to increase the size of the anode. This results in a lower resistance to earth which effectively increases the current delivery from the galvanic anode. The efficiency of the anode is also improved.

3.2.5 DC Decoupling Devices

Galvanic anode systems can be effectively applied to buried pipes that are coated and electrically isolated. If insulating devices are installed and the piping is electrically isolated, consideration should be given to using solid state DC decoupling devices across the insulating joints. Solid state de-couplers may be used in conjunction with insulating joints to improve the effectiveness of CP on buried piping by isolating the copper grounding. The decoupling devices are installed above grade with cables and/or clamps that are bonded to both sides of the insulating device. The DC de-coupler will act as an open circuit for DC and as a short circuit for AC and lightning surges; thereby maintaining effective grounding while ensuring that the CP current is delivered to the piping system. In this manner, the bare copper grounding system is not competing with the piping for CP current. Installation of these devices will also allow effective use of indirect survey techniques that are used to locate coating flaws and corrosion activity on the buried piping. However, since effective isolation of existing buried piping systems may be difficult to accomplish (due to multiple ground connections), DC de-couplers may only be applicable where new piping systems are being designed and constructed. Figure 3-11 provides a photograph of a solid state DC de-coupling device that is installed across an above grade pipeline insulating flange.



Figure 3-11
Solid State De-Coupler at Pipeline Insulating Flange
(Source: Dairyland Electrical Industries)

3.3 Comparison of CP System Characteristics

In most cases, the impressed current system is designed to deliver relatively large currents from a limited number anodes and the galvanic system is designed to deliver relatively small currents from a larger number of anodes. Each method of applying cathodic protection has characteristics that make it unique or applicable to a structure. At nuclear power plants, because of the grounding effect and significant current requirements for cathodic protection, the impressed current method is almost always used. Table 3-3 provides a comparison of both systems.

Table 3-3
Comparison of CP System Characteristics

Galvanic Anode System	Impressed Current System
No external power required	External power source required
Simple design	More complex design
Fixed driving voltage	Adjustable driving voltage
Limited current (typically 10-50 mA)	Larger current (typically 10-100 Amps)
Typically used with electrically isolated, well coated structures	May be used with electrically isolated structures and grounded structures that are coated or bare
Typically used in soils with lower resistivity	May be used in low resistivity or high resistivity soils
Lower maintenance	Higher maintenance
Does not cause stray current corrosion	Stray current corrosion can be generated on isolated structures that are in close proximity to the anode groundbed

3.4 Test Stations

When evaluating CP systems for buried piping at nuclear power plants, test stations are needed to monitor the effectiveness of the CP systems. Test stations and test station wiring schematics should include sufficient detail to provide accurate identification of the structures, buried piping, coupons and permanent reference electrodes, where applicable. The test station housing should have an external identification label and the test station wiring should include identification tags that clearly identify the purpose and function of the wiring. Test station wiring that is connected to the plant grounding should be done only after electrical continuity with the buried piping has been determined. Test stations should be placed at a sufficient number of locations to provide a representative assessment of the pipe-to-soil potentials that are used to gauge CP system performance.

Test station wiring should not carry cathodic protection or other current loads that can cause extraneous voltage drops in the wiring resulting in erroneous data. The use of buried “permanent” reference electrodes, IR-drop free coupons, and/or corrosion rate (electrical resistance) probes at or near the pipe depth can increase the accuracy of the potential measurements and other data that are used to gauge CP system performance.

Test stations may include post mounted, wall mounted, junction boxes and flush-to-grade assemblies. Test station designs should be as simple as possible to facilitate easy access for routine surveillance. Test stations should also facilitate accurate repeat measurement of the structure-to-soil potential, thereby allowing trending of data over time. Placement of these devices is particularly valuable in accessing system effectiveness for deeper piping and congested areas where electrical shielding can be an issue.

The measurement of the pipe-to-soil potential using a portable reference electrode placed at grade over the pipe may also be used for this purpose. In certain areas the potential at grade may be a mixed potential that is dominated by other structures, such as the copper grounding grid. These readings may not be representative of the true pipe-to-soil potential at pipe depth, especially if the pipe is deep in the ground.

Depending on the location within the plant, test stations may consist of:

- *Test Points* with test lead wires to the structure, with or without "permanent" reference electrodes at pipe depth
- *Test Wells* which facilitate measurement of the structure-to-electrolyte potential at pipe depth using a portable reference electrode
- *Soil Access Points* or soil boxes which facilitate measurement of the structure-to-electrolyte potential at grade using a portable reference electrode
- *Coupon Test Stations* with IR-drop free coupons, which facilitate polarization and depolarization testing and other corrosion and CP related measurements, and
- *Electrical Resistance (ER) Probes*, which facilitate measurement of the corrosion rate by monitoring the change in cross sectional resistance of a buried conductor over time

3.4.1 Test Points

Test points may consist of above grade or flush mounted test lead wires that are connected to the pipe or to a structure that is electrically continuous with the pipe, such as station ground. A permanent copper-copper sulfate reference electrode (CSE) may be installed at a test station to facilitate measurement of the structure-to-electrolyte potential. Test lead wires from the structure and reference electrode should terminate on the terminal board inside the test station head. Test stations may also be used to connect galvanic anode lead wires to the structure using test lead wires. Figure 3-12 provides a detail of a test station for buried piping with a permanent reference electrode.

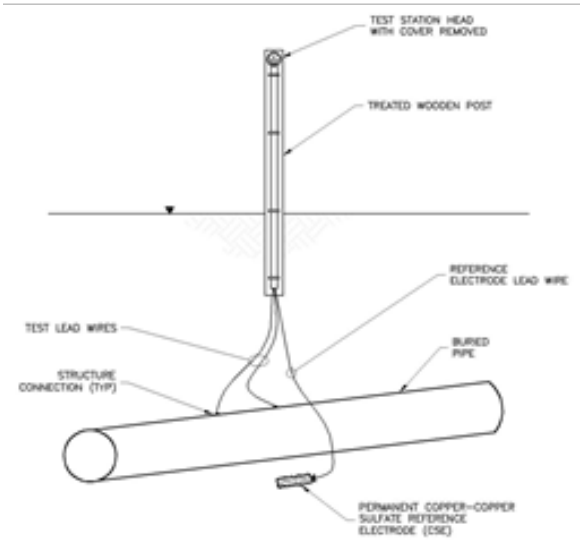


Figure 3-12
Test Station with Permanent Reference Electrode

3.4.2 Test Wells

A test well will typically consist of 2-in. diameter PVC pipe (with perforations or slots at the base) that is installed vertically in a hole adjacent to the buried pipe. The PVC pipe is of sufficient length to allow measurement of the structure-to-soil potential using a portable reference electrode at pipe depth. Prior to taking the potential measurement, potable water is added to the test well and the portable reference electrode assembly is lowered to the structure depth inside the tube using a submersible adapter.

3.4.3 Soil Access Points

Soil access points or test boxes may be used to evaluate shallow pipes that are buried beneath asphalt or concrete using a portable reference electrode. The housing at the base of the test box is open to allow placement of the reference electrode in the soil.

3.4.4 Coupon Test Stations

Coupon test stations may be incorporated at critical test station sites to facilitate additional corrosion and CP system monitoring. Critical sites may include pipeline crossings, sites where copper grounding is in close proximity to the pipe, sites where the pipe enters a concrete building wall and sites where functional testing indicates lower polarization values and higher current drain from the anode system. NACE Standard RP0104-2004 “The Use of Coupons for Cathodic Protection Monitoring Applications” provides guidance in using coupons with CP systems.

Coupon test stations may serve several functions. They are particularly useful for structures utilizing polarization or depolarization criterion. Coupons should be manufactured of the same material as the pipe being analyzed. Although carbon steel coupons are commonly used for most carbon steel piping systems, cast iron coupons may be used for water lines and fire protection systems that use cast iron piping.

Depending on the specific circumstances, various types of coupon designs may be used. Figure 3-13 provides a typical detail for an above grade coupon test station. Figure 3-14 provides a detail for a flush coupon test station in a plant environment. This type of test station consists of a 3 in (7.6 cm) diameter PVC reference tube with coupons fitted at the base of the tube. The structure wires and coupon wires are brought up inside the tube to the test station terminal board. For this design two (2) coupons are typically provided: 1) polarized carbon steel coupon to be connected to the structure receiving CP, and 2) native (free corroding) steel coupon that is electrically isolated.

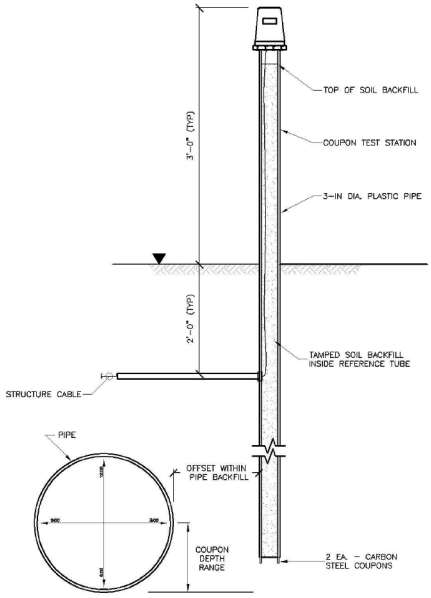


Figure 3-13
Above Grade Coupon Test Station

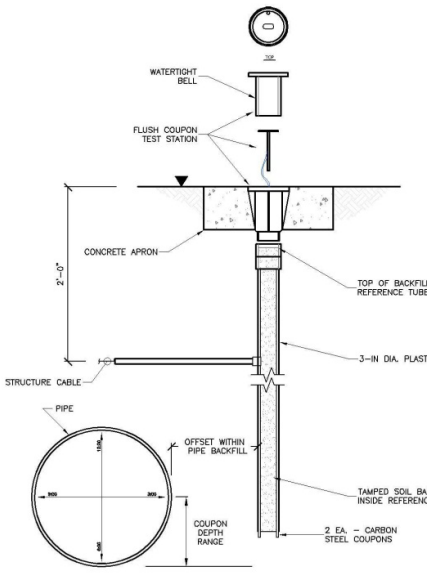


Figure 3-14
Flush-to-Grade Coupon Test Station

If possible the coupons at the base of the reference tube should be installed above the pipe or adjacent to the pipe in the same backfill as the pipe. If the coupons are not installed in the same backfill as the pipe, then the data from the coupons will not accurately reflect the soil conditions that are germane to the pipe. Furthermore, if the coupons are installed in gravel backfill that is free of water, a high contact resistance and extremely low (negligible) corrosion rate can be expected from the test data. To facilitate measurement of the structure-to-soil at the base of the coupon test station the reference tube is filled with clean native soil to allow placement of a portable reference electrode inside the top of the tube. Permanent reference electrodes may also be incorporated at the base of the assembly for additional measurement capabilities.

The polarized (CP) coupon allows connection to the CP system on the structure, thus simulating a similar-sized bare area of the structure's surface, such as a holiday in the coating. The CP coupon may be disconnected from the circuit during functional testing, and its Instant-Off potential measured. The potential of the CP coupon is monitored and the depolarization value calculated. A second, freely corroding (native) coupon is used to measure the free-corrosion (native) potential of the structure in open-circuit conditions. Corrosion rates may be calculated using the linear polarization resistance (LPR) method and in conjunction with polarization data, the expected corrosion rate with cathodic protection applied can be estimated. LPR is an electro-chemical method of measuring the corrosion rate of a sample specimen in mils per year (mpy). A third copper coupon (copper ground rod) can be installed next to the test station to simulate the effects of the dissimilar metal coupling to station ground. The advantages of using coupon test stations include:

- Verify CP system effectiveness
- Allow measurement of the ON and Instant-Off potential without rectifier interruption
- Facilitate polarization and depolarization testing
- Allow measurement of the native potential (to an isolated coupon)
- Permit calculation of current density
- Allow measurement of free (not cathodically protected) corrosion rate (mpy) using one of the steel coupons, and
- Can be used to simulate effects of copper grounding and dissimilar metal couplings by the addition of a third copper coupon

3.4.5 Electrical Resistance (ER) Probes

Electrical resistance (ER) probes are corrosion monitoring devices that rely on the changes in the cross sectional area of a buried electrical resistance conductor that is exposed to the soil environment. A portable ER corrosion rate instrument is used to collect the corrosion rate data. The probes are typically manufactured in a sealed injection molded assembly and are available in a variety of geometric shapes and configurations to facilitate the anticipated corrosion rate and probe life. They are also provided with a "check" element that is sealed from the environment. The "check" element is a reference element that provides confidence in the continued performance of the corrosion sensor. ER probes are designed for buried structures that are cathodically protected or not. When electrically connected via an external grounding cable, the probe provides a continuous record on the effectiveness of the CP system under its operating conditions. The lead may be installed at the probe or connector end, whichever is most

convenient. A zero (0) or close to zero corrosion rate measurement would be indicative of effective cathodic protection. When not connected to the structure, it monitors the corrosivity of the soil or environment surrounding the buried pipe. The primary corrosion rate mechanism monitored by this method is general corrosion rate. The ER probe does not provide corrosion rate accuracy with respect to pitting corrosion.

3.5 Permanent Reference Electrodes

As mentioned above, permanent reference electrodes allow measurement of the structure-to-soil potential of buried piping in congested areas or in areas that are inaccessible. The location and placement of the permanent reference electrode is important, so it accurately represents the potential of the pipe. Permanent reference electrodes should be positioned in close proximity to the buried pipe (typically with several feet) and in the same backfill as the pipe, but not touching the pipe. They are typically installed in areas that are hard to access.

Historically, the design life of permanent reference electrodes is relatively short due to contamination of the electrode by the electrolyte. However, permanent reference electrodes are now available that provide longer design life (reported to be 20-40 years). The newer reference electrodes also minimize leakage of the electrode filling solution into the soil and therefore the potential is not affected by the electrolyte elements.

For buried structures in soil, the copper-copper sulfate reference electrode (CSE) is most commonly used. For piping that is buried in saline soils, or for piping that is submerged in brackish water or seawater environments, the silver-silver chloride (Ag-AgCl) reference electrode is used. Measurements using other types of reference electrodes are often converted to those of copper-copper sulfate.



Key Technical Point

Copper sulfate electrodes are the most commonly used reference electrodes. Measurements using other types of reference electrodes are often converted to those of copper sulfate.

3.6 Number and Location of Test Stations

Test stations have traditionally been used to electrically examine buried pipelines to determine if cathodic protection is adequate, as well as making other measurements for corrosion control. Normally access to buried pipelines is provided via test leads which serve as the connection point for measuring the structure-to-soil potential. At least one test station per rectifier that is connected directly to the buried piping and strategically located is advised and often several test stations are required to provide representative data. Test stations should also be installed at other critical locations such as road crossings, pipeline crossings, congested piping areas, building entrances, water crossings, insulating joints and areas where copper grounding is in close proximity to the buried piping. Test stations may also be used to connect galvanic anodes to the piping.

At nuclear power plants a station ground conductor that is above grade may serve as an electrical connection point for measuring the pipe-to-soil potential. When using a station ground for a

potential measurement, electrical continuity between the ground conductor and piping should be confirmed. As stated above test stations may consist of test points, test wells, soil access points, coupon test stations and test stations fitted with ER probes. Each has its own specific purpose and function. The number and location of test stations is therefore part of the CP design process. A sufficient quantity should be installed so that representative monitoring of the CP system performance can be provided. Additional test stations may be required for monitoring safety-related piping. Test stations will often serve as the permanent monitoring sites for bi-monthly inspections and annual corrosion survey work.

Test stations and monitoring devices are relatively inexpensive compared to the cost of excavation. Test stations with permanent reference electrodes or other corrosion monitoring devices should be installed whenever buried pipes are exposed.

As a rule of thumb, test stations should be considered for buried piping systems that are subject to the following conditions:

- Sites where buried copper grounding crosses the pipe or is in close proximity to the pipe
- Sites where the pipe enters a concrete foundation wall or underground vault
- Congested areas where multiple piping systems exist in close proximity to one another
- Pipeline crossings
- Road crossings
- Water crossings
- Insulating joints
- Pipes that are deeply buried in the ground and/or inaccessible
- Sites where the piping has experienced previous external corrosion damage
- Sites where the piping runs beneath asphalt or concrete
- Sites where test lead wires are required for measuring the structure-to-soil potential
- Sites where functional testing indicates lower polarization values and higher current drains from the anode system, and
- When excavations are made on buried piping

4
CP SYSTEM TESTING AND ANALYSIS

A good source for cathodic protection survey procedures can be found in NACE Publication No. 37590, *Cathodic Protection Survey Procedures*, by W. Brian Holtsbaum. The following section provides a guideline for CP system testing and analysis.

4.1 Structure-to-Soil Potential Measurements

Measurement of the potential between a pipeline and a stable reference electrode is the most frequent test performed in the corrosion industry. All discussions in this guide that deal with structure-to-soil potential measurements will be referenced to a copper/copper-sulfate reference electrode (CSE). Pipe-to-soil potential measurements are performed by placing the reference electrode so that it is in contact with the soil over the pipeline. The porous plug, with cap removed, should be in firm contact with moist earth. This may require "digging-in" at places where the surface of the soil is dry. In extremely dry conditions, it may be necessary to moisten the earth around the electrode with potable water to obtain good contact with the soil. In areas of asphalt or concrete it may be necessary to drill small (1/2" diameter) holes through the asphalt or concrete to allow contact with the underlying soil. The hole is then filled with water to form a bridge (electrolytic path) between the portable reference electrode and the soil. In areas where access is difficult, permanent reference electrodes may be installed in the soil for measuring the structure-to-soil potential.

Portable reference electrodes should be cleaned and tested for accuracy prior to using. The engineer or technician should ensure that the reference tube is filled with copper sulfate crystals and that the rod is fully burnished with a non-metallic abrasive. Deionized water should be added if necessary. Testing for accuracy should be made to another reference electrode, which is used only as a standard. Measurements shouldn't be taken when the ground is frozen.

For the purposes of standardized convention in this document the reference electrode will be connected to the negative terminal of a high-impedance (minimum 10 megaohm) voltmeter and the positive terminal to the piping (via a test point terminal or direct contact with the piping or station ground). A standard detail for a pipe-to-soil potential measurement is shown in Figure 4-1.

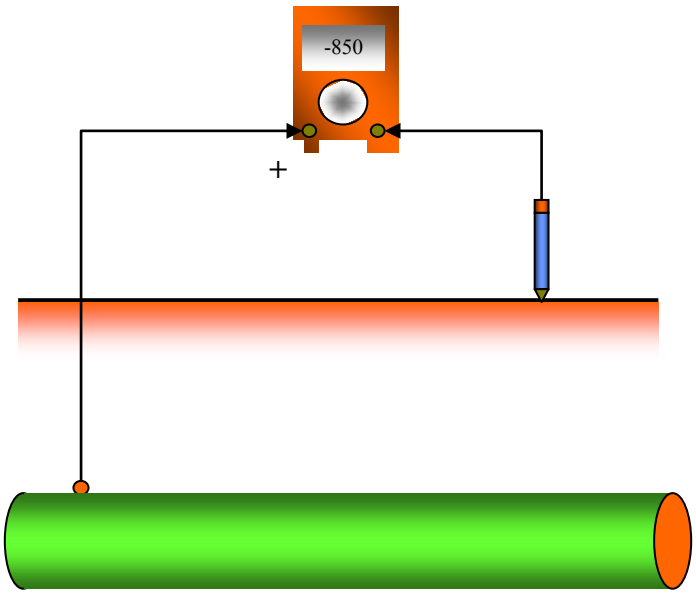


Figure 4-1
Pipe-to-soil Potential Measurement

4.2 Close Interval Survey

The principle involved in the close interval survey (CIS) is presented in Figure 4-2 and shows potential readings taken on a continuous basis (typically at 3 to 5 ft intervals) over a buried pipeline. Typically, a measuring device, with light wire for continuous contact to the pipeline, is used with a data logger to capture data as the survey is being performed. The location of each electrode position is recorded with the observed potential. Test points, features and other pipeline appurtenances are also entered into the data logger. GPS data may also be entered so that alignment of the data can be provided. NACE Standard SP0207-2007 "Performing Close-Interval Potential Surveys and DC Surface Potential Gradient Surveys on Buried or Submerged Metallic Pipelines" provides guidance regarding the use of close interval surveys.

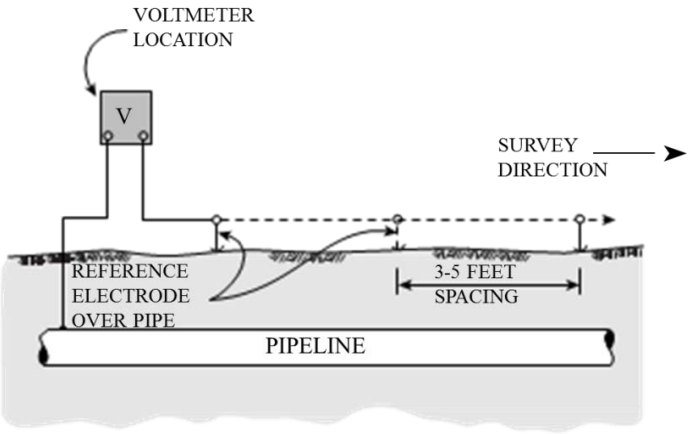


Figure 4-2
Close Interval Survey
(Source: Peabody's Control of Pipeline Corrosion)

To illustrate information that can be obtained with a close interval survey (CIS) with CP, Figure 4-3 represents plotted data taken from an actual field at a nuclear power station on a well-coated pipeline with marginal protection. Prior to commencing the potential survey a rectifier influence survey should be conducted to determine what current sources (or rectifiers) are contributing to polarization of the pipe segment. Once identified, all current sources are interrupted using GPS synchronized current interrupters. Both "on" and "instant-off" polarized potentials are taken along the pipeline segment. The interruption cycle is typically three (3) seconds close-circuit (On) and one (1) second open-circuit (Off), although longer interruption cycles may be used. The plotted data again does not form a smooth curve even when taken on a cathodically protected pipeline. Depressions in the plot (least negative potential) indicate locations where CP may not be adequate, areas of electrical grounding, contacts with foreign structures or areas of possible coating damage.

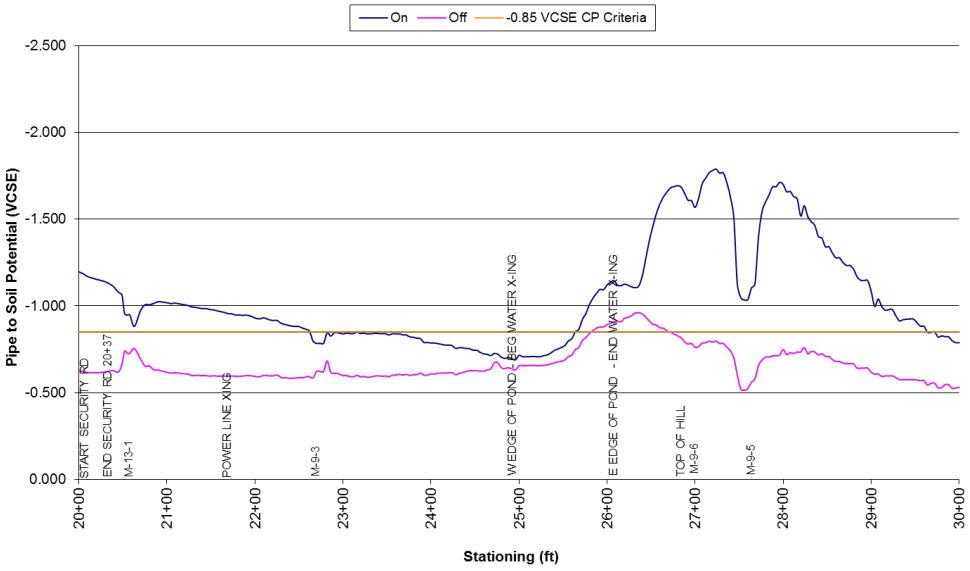


Figure 4-3
Example of Interrupted CIS Data

In conjunction with the survey, stationary data loggers are placed at anticipated daily CIS midpoints and programmed to record the pipe-to-soil potential throughout the duration of daily CIS activities. The data loggers are used to confirm interruption synchronization, monitor for rectifier power problems, and monitor for possible dynamic stray current activity. Waveform analysis of the structure-to-soil potential is also recorded at the beginning of each survey to confirm that a true instant-off potential is being captured. Near ground (NG), far ground (FG) and IR drop measurements are obtained where it is practical at the CP test stations and where pipe access is available. If the IR drop is considerable then a new test point connection should be made to the structure and the survey continued. CIS is often performed by vendors that specialize in potential surveys and external corrosion direct assessment (ECDA) of cross country pipelines.[14]

[14] ANSI/NACE SP0502 "Pipeline External Corrosion Direct Assessment Methodology", NACE International, Houston, TX.

4.3 Soil Resistivity Measurements

The soil resistivity measurements are used to determine the relative corrosivity of the environment and are important in the design of anode groundbeds. The Wenner four pin method (ASTM Standard G57) is the most commonly used method for soil resistivity measurement.

With the Wenner array, the soil resistivity is evaluated at various depths (such as 2.5 feet, 5.0 feet, 7.5 feet and 10.0 feet depths) using a Nilsson Model 400 Soil Resistance Meter or similar equipment. A circuit diagram of the Wenner four electrode soil resistivity measurement is shown in Figure 4-4.

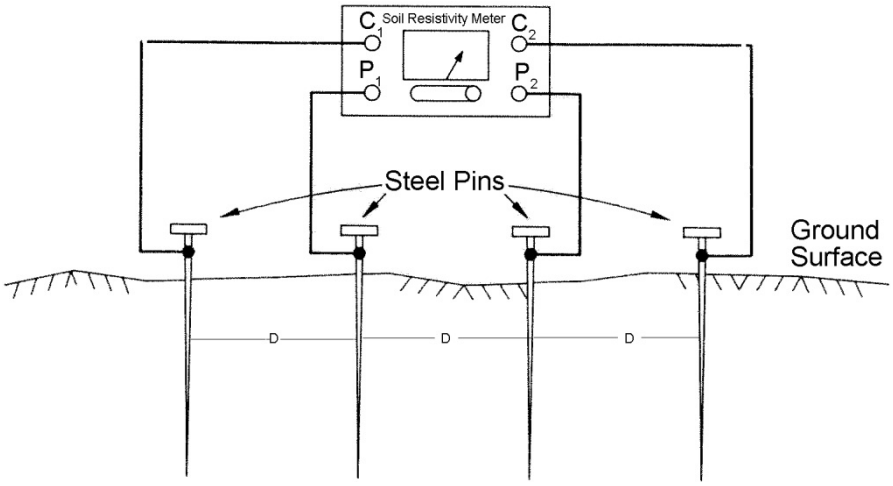


Figure 4-4
Wenner Four Electrode Method

When using the Wenner array, it is important that the resistivity measurement be taken in open areas that are not influenced by buried metallic structures. A rule of thumb is to take readings perpendicular to the structure with a minimum offset that is twice (2X) the pin spacing. This requirement is shown in Figure 4-5. In congested plant areas this technique may not be possible and alternate methods may need to be used, such as measuring the resistivity of soil samples in a Soil Box or by using a single probe Collins Rod.

Once the resistance of the soil at a particular depth has been determined, it is converted to resistivity by multiplying the value by a constant (191.5) and the electrode spacing (depth) in feet. The calculated value is the resistivity in ohm-centimeter

$$\rho\ (\Omega\ cm) = R\ (\Omega) * depth\ (ft) * 191.5 \qquad \text{Eq. 4-1}$$

The soil resistivity determined from the Wenner four pin method is the average (or apparent) soil resistivity of a hemisphere of earth, where the radius of the hemisphere is “d”, or the distance between the inside pins as shown in Figure 4-5.

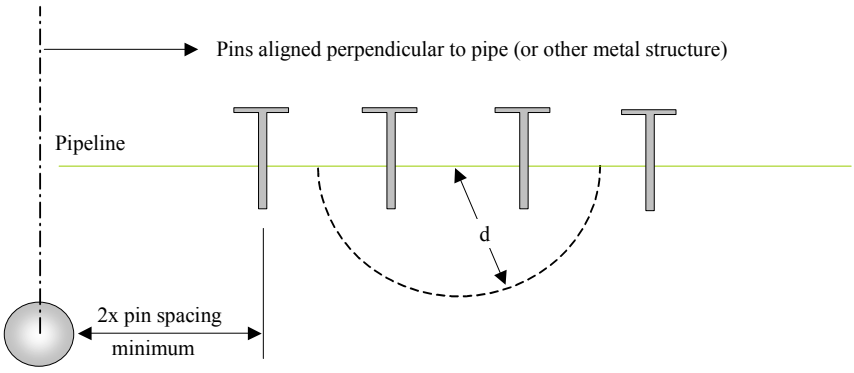


Figure 4-5
Pin Alignment Perpendicular to Pipe

When it is not possible to measure soil resistivity using the Wenner 4-pin method, (or in cases where the pipe was backfilled using non-native soil) soil samples taken from excavations or bore holes can be measured in a soil box. As shown in Figure 4-6, metal contacts in each end of the box are used to pass current through the sample. Potential drop is measured across probes inserted into the soil. When using a standard soil box with a conversion factor of x1 and a Nilsson Model 400 Soil Resistance Meter, the direct measurement of resistance is equivalent to soil resistivity in ohm-cm. If the samples are to be measured at a later date, drying out of samples should be minimized by using sealed plastic bags. If the samples have dried out and re-wetting is required, deionized water should be used to minimize outside influence on the results. Tamping of soil in the soil box to a different compaction may also provide different results.

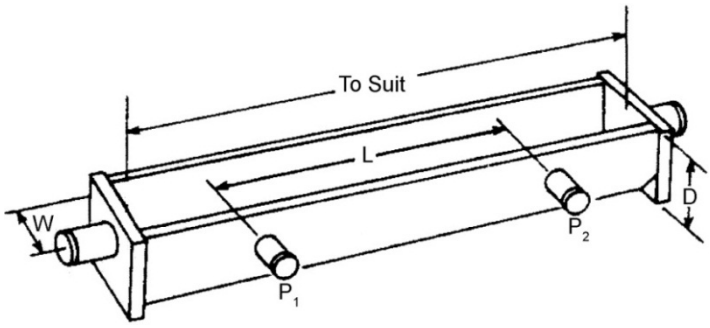


Figure 4-6
Soil Box for Determination of Resistivity

4.4 Anode Resistance Measurements

Knowledge of the anode-to-earth resistance is an important quality control test during installation of the anode groundbed. Monitoring the anode groundbed resistance over time will also provide an indication if the anode bed is failing. An increase in resistance may indicate dry-out of the groundbed (through electro-osmosis) or consumption of the anodes. Anode resistance is measured using a soil resistance meter, such as the Nilsson Model 400 instrument. For this test the C1 and P1 terminals of the meter are connected to the anode lead and the C2 and P2 terminals to the structure. The resistance is measured after the dial has been adjusted and the

needle is “nulled”. The relative anode bed resistance may also be calculated by dividing the rectifier voltage (Volts) by the rectifier current (Amps), or R = E/I.

4.5 Anode Current Measurements

Anode currents are typically measured using shunts in a junction box. This design allows measurement of individual anode currents so that anode performance can be monitored and problems identified. A standard junction box may be provided with terminals and shunts. The shunts are pre-calibrated to measure current flow using a voltmeter (millivolt drop). The shunts may also be connected to an ammeter and the currents are measured for individual leads using a selector switch. Anode currents may also be measured using a clamp-on DC ammeter; however this method is not as accurate. When measuring the millivolt drop across a shunt, the test leads should be placed on the inner calibration points or prongs. The shunt rating is typically written on the side of the shunt and Ohms Law (I=E/R) is used to calculate the current. Resistors may also be added in the junction box to control the current. Table 4-1 provides typical shunt ratings for cathodic protection work.

Table 4-1
Typical Shunt Ratings

Shunt Type	Capacity	Resistance (Ohms)
JB	8	0.01
RS	8	0.01
SO	5	0.001
SS	25	0.001
SW	5-200	0.002-0.01

4.6 Structure Drain Measurements

In some situations the return current is measured in the rectifier system negative cables from the structures to which they are connected. This measurement provides an indication of the current distribution to the piping system and structures receiving cathodic protection. The current drain measurements are typically made in junction boxes specifically designed for this purpose or at the rectifier using shunts or a clamp-on DC ammeter placed in the system negative cables.

4.7 Electrical Continuity Testing

When cathodic protection current is applied through the soil to the buried piping, metallic structures that are not continuous with the current return path may receive stray current interference and corrode at an accelerated rate. The zone of influence and severity of this condition is dependent on the relative location of the anode system with respect to the buried metallic structure, applied current from the CP system and voltage gradients that are developed from the anodes. Continuity testing should be performed upfront during the design phase and also during the construction phase as structures are uncovered during excavation. Most often, all piping at nuclear power plants is tied to station ground and therefore bonding is typically not necessary. However, certain structures may require more detailed testing to ensure that continuity was established. These structures may include cast iron and ductile iron pipes that are

used for potable water, fire water and sanitary where bell and spigot joints are used, and concrete cylinder pipe (PCCP). Bonding is typically required across bell and spigot (gasketed) joints and bolted (mechanical) joint assemblies. Concrete cylinder pipe may also be manufactured in such a manner as to establish metal continuity between the metallic components of the pipe and the joints. The PCCP may contain a longitudinal steel strap that maintains electrical continuity between the steel components and also serves to reduce longitudinal resistance of the tensile wires. Corrugated metal storm drains, catch basins, pipe bollards and secondary fencing should also be evaluated for continuity.

Resistance tests and voltage drop tests typically do not provide sufficient information to properly evaluate continuity of buried metallic structures, as the parallel conductance of the soil may distort the reading. Continuity testing should consist of applying direct current from an anode source, interrupting the current and measuring the On/Off structure-to-soil potential using a portable copper-copper sulfate reference electrode. The reference electrode should remain in a stationary (fixed) position over the pipe and structure-to-soil potentials are recorded with the structure lead moved from one ground connection to another. Electrical continuity is indicated when the potential measurements and changes in potential measurements with the applied current are approximately equal, regardless of the point of connection to the structure. If electrical continuity has not been established and isolated joints are present in the buried piping system, then the CP current may result in stray current interference and accelerated corrosion can be expected on the discontinuous members.

4.8 Stray Current Testing

Stray currents from one structure's cathodic protection system can affect the CP system on a nearby structure if the structures are not inter-connected or electrically isolated. Dynamic stray current activity may also result from DC welding operations at the plant. During external corrosion surveys, personnel should be alert for electrical or physical observations that could indicate interference from a foreign source such as:

- Structure-to-electrolyte potentials that are more electro-positive than normal
- Structure-to-electrolyte potentials that vary or fluctuate rapidly indicating dynamic stray current activity
- Localized pitting in the area near or immediately adjacent to a foreign structure, and
- Damage of external coatings in a localized area near a foreign anode bed or near any other source of stray direct current

Tests must be performed to identify the stray current interference so that protective measures can be taken. A current interrupter is inserted into the cathodic protection circuit of the current source that may be causing the stray current problem. The structure-to-soil potential of the nearby structure is then measured with the current cycled on and off. If the potential of the nearby structure becomes more electro-positive with the current on, stray current interference is indicated and corrective measures are required.

When interference is found, it is necessary to determine if the affected area or point of crossing from one structure to the other is actually the point where current discharge is greatest. This can be done by moving the reference electrode at the affected area or crossing. Generally, the point of maximum current discharge corresponds to the point of greatest voltage change.

Stray current corrosion of buried piping is typically not an issue at nuclear power plants because of the common grounding which provides continuity throughout the piping system. The current that is produced by one rectifier system may overlap on adjacent piping in another part of the plant without any adverse effects. If insulating devices are employed on sections of buried piping, then stray current testing should be performed and protective measures taken if interference conditions are present. Protective measures may include attachment of an electrical bond or supplementary CP. Often if the condition is severe, a corrosion consultant who specializes in stray current testing and mitigation should be employed to investigate the condition, perform stray current testing and provide recommendations for mitigation.

4.9 Start-up Testing and Commissioning

After the anode groundbeds, rectifiers, DC cabling, system negative connections, test stations and the AC power supply to the rectifiers have been installed, start-up testing and commissioning of the CP systems should be performed. The following serves as guideline for start-up testing and commissioning of an impressed current cathodic protection system for buried piping at a nuclear power plant:

- Obtain native structure-to-soil potential measurements at test stations and other critical locations, where applicable.
- Verify correct polarity hook-up of the positive and negative cables at the rectifier DC output terminals. Verify that all wiring is properly identified and terminated in the rectifiers and junction boxes. Verify the rectifier cabinet is properly grounded. Incorrect termination of the positive and negative cables will result in corrosion of the structure rather than the anode. Double verification is always required for this start-up procedure.
- Obtain anode-to-earth resistance and anode-to-cathode voltage measurements.
- Energize rectifier at lowest tap setting. Measure DC output voltage and current. Verify accuracy of rectifier meters with portable test instrumentation.
- Increase output to target current output based on design calculations.
- Initiate interruption cycle in the rectifier or rectifiers that are influencing the structure or structures being protected. For multiple rectifiers, ensure GPS synchronization of current interrupters. Depending on the anode groundbed location a rectifier influence survey may be required.
- Obtain “On” and “Instant-Off” structure-to-soil potentials at test stations and at other critical locations.
- Verify that no short circuits exist between the anode bed and structure.
- Increase or decrease rectifier output by changing tap settings until target protection levels have been achieved at test stations and other critical locations.
- Stop interruption cycle and allow system to polarize structure for at least 24 hours.
- Obtain DC output voltage and current readings at rectifier and calculate the anode groundbed resistance.
- Obtain AC input voltage and current readings and calculate the rectifier efficiency.

- Measure anode currents at all junction boxes using the provided shunts.
- Measure structure drain currents at junction boxes and rectifier system negative cables.
- Obtain structure-to-soil potentials at all test stations and other critical locations and readjust rectifier output as necessary to achieve required protection. The final commissioning survey may also include an interrupted close interval survey (CIS) over the affected piping.
- If the nuclear power plant is located in close proximity to a foreign structure with cathodic protection (such as a buried transmission pipeline), notifications should be submitted to the local stray current corrosion interference committee and cooperative interference testing conducted if necessary. This may require interruption of all influencing current sources at the plant.
- Prepare and submit a final post installation testing and commissioning report to include a summary of findings, tabulation of test data, aligned CIS data where applicable, recommended operating levels, recommendations for system monitoring and maintenance, and recommendations for supplemental cathodic protection if required.
- Provide training to plant engineering and maintenance personnel regarding the operation and maintenance of the impressed current system.



Key Technical Point

Verify correct polarity hook-up of the positive and negative cables at the rectifier DC output terminals. Incorrect termination of the positive and negative cables will result in corrosion of the structure rather than the anode. Double verification is always required for this start-up procedure.

The following serves as guideline for start-up testing and commissioning of a galvanic anode cathodic protection system for buried piping at a nuclear power plant:

- Where applicable, verify that the insulating joints in the piping system are effective and the buried piping system is effectively isolated from station ground.
- Obtain native structure-to-soil potential measurements at test stations and other critical locations.
- Verify that all wiring is properly identified and terminated in the test station or junction box.
- Obtain anode resistance and anode-to-cathode voltage measurements.
- Measure anode currents at all test stations or junction boxes using the provided shunts.
- Obtain “On” and “Instant-Off” structure-to-soil potentials at test stations and at other critical locations. The final commissioning survey may also include a close interval survey (CIS) over the affected pipelines.
- Prepare and submit a final post installation testing and commissioning report to include a summary of findings, tabulation of test data, aligned CIS data where applicable, recommendations for system monitoring and maintenance, and recommendations for supplemental cathodic protection if required.

- Provide training to plant engineering and maintenance personnel regarding the operation and maintenance of the galvanic anode system.

4.10 Criteria for Cathodic Protection

NACE SP0169-2007 "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" provides a guideline for cathodic protection criteria of buried metallic piping systems. Acceptance criteria for cathodic protection of steel, copper and aluminum piping are also given in the ISG GALL Report, Revision 2, Aging Management Program XI.M41. NACE RP0100-2004 "Cathodic Protection of Prestressed Concrete Cylinder Pipelines" provides a guideline for cathodic protection of prestressed concrete cylinder pipe (PCCP).

4.10.1 Criteria for Steel and Gray or Ductile-Iron Piping

NACE cathodic protection criteria for steel and cast iron piping can be summarized below:

a) A negative polarized (instant-off) potential of at least -850 mV (CSE) with CP current applied.

b) A negative polarized (on) potential of at least -850 mV (CSE) accounting for voltage (IR) drop.

c) A minimum of 100 mV of cathodic polarization between the structure and a reference electrode contacting the electrolyte as measured by the formation or decay of polarization.

The polarized -850 mV criterion is the most commonly used criteria for cathodic protection of buried and submerged metallic structures and is one of three identified for steel and cast iron piping referenced in NACE SP0169. This criterion states that adequate protection is achieved when a negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode (CSE) is achieved. The polarized potential can be defined as the potential across the structure/electrolyte interface that is the sum of the corrosion potential (E_{corr}) and the cathodic polarization. The polarized potential is measured directly after interruption of all current sources and is often referred to as the "Off" or "Instant-Off" potential.

Unlike the -850 mV "On" criterion with cathodic protection current applied, the -850 mV polarized potential criterion accounts for the IR drop error introduced as a result of voltage drops in the electrolyte (soil) and the metallic return path in the measuring circuit. Limitations for this criterion include the requirement that all sources of direct current must be interrupted simultaneously. If multiple rectifiers are used and all the piping is electrically common, a large number of current interrupters may be required. However, as stated above, the polarized -850 mV criterion is widely applied to buried and immersed metallic structures and is also applicable to piping in mixed metal systems such as nuclear power plants.

The 100 mV criterion is most commonly used for structures that are bare or poorly coated where it is difficult to achieve the -850 mV criterion. NACE Standard SP0169 "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" allows for the formation or decay of polarization to be measured to satisfy this criterion. The procedures that are typically used for conducting polarization measurements when using this criterion are outlined in NACE Publication 35108 and NACE Standard TM0497 "Measurement Techniques related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems". For measuring either development or decay of polarization, cyclic interruption of the CP source(s) is usually

performed to obtain valid Instant-Off structure-to-soil potential measurements. The development method of polarization growth involves interrupting the CP current source(s) and measuring the Instant-Off potential (see Figure 4-7). If the difference between the Instant-Off potential and the native potential (Ecorr) is equal or greater than 100 mV, then the 100 mV cathodic polarization criterion is satisfied.

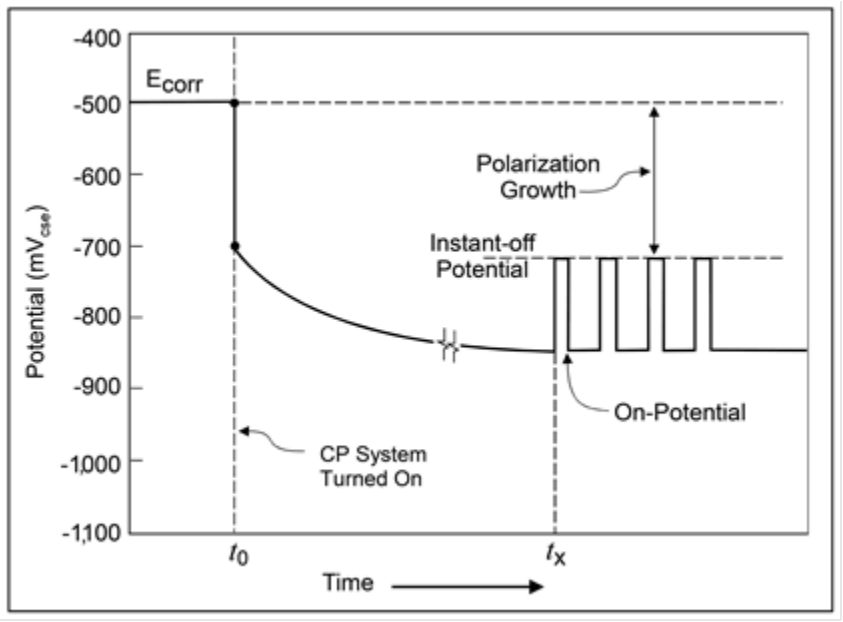


Figure 4-7
Determination of Polarization Formation
(Source: NACE Publication 35108 "One Hundred Millivolt (mV) Cathodic Polarization Criterion")

The time frame to allow for full depolarization of a structure is dependent on several conditions including the structure's coating quality, environmental conditions including oxygen concentration and CP system operation. In oxygen depleted environments full depolarization may take weeks or months to observe. In aerated soils full depolarization may take several days to observe. To determine the time required for a structure to fully depolarize, one or more data loggers should be employed to measure the structure-to-electrolyte potential. The power sources are turned off and the structure-to-electrolyte potential is monitored using the data loggers until little or no change in potential is observed. Coupons are often used in situations where it is difficult to obtain accurate native potential measurements.

The decay method for determining the level of polarization is a very common technique, since it is applicable to structures that have been receiving CP for a long period of time. The measurement procedure for the decay method employs the cyclic interruption of the CP current source(s) in order to obtain the Instant-Off polarized potential. The CP system is then turned off and the decrease in potential is monitored until the rate of change in potential with time (dV/dt) approaches zero. If the depolarized potential at time "tx" is more electropositive by 100 mV or more than the Instant-Off potential, then the 100 mV polarization criterion is satisfied (see Figure 4-8). In practice the potentials are typically taken at different times, at the same location and the values are subtracted from the Instant-Off potential to obtain the value of polarization decay. The reference electrode is typically placed at the same location as the previous survey to minimize measurement error.

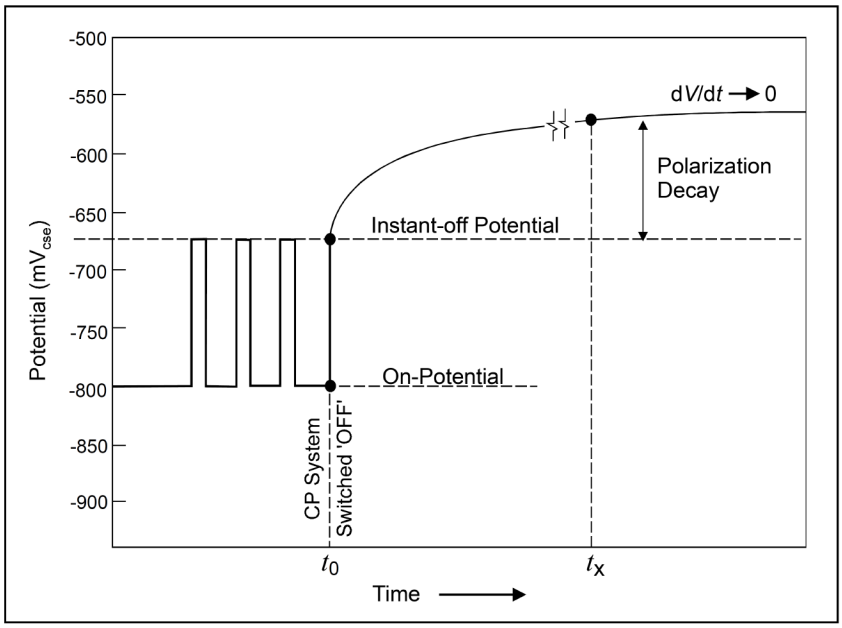


Figure 4-8
Determination of Polarization Decay
(Source: NACE Publication 35108 "One Hundred Millivolt (mV) Cathodic Polarization Criterion")

There has been considerable debate by experts in the CP industry over the use of the 100 mV cathodic protection criterion when applied to structures having different metals interconnected. NACE SP0169 stipulates that for dissimilar metal piping a negative voltage between all pipe surfaces and a stable reference electrode contacting the electrolyte equal to that required for protection of the most anodic metal in the system should be maintained. The major concern is that the difference in potential between the anode and cathode sites in a mixed-metal network can be quite large (e.g. carbon steel-copper, carbon steel-stainless steel, carbon steel-reinforcing steel, etc.). As stated above a large potential difference can also exist on carbon steel piping near concrete foundation walls where the piping and sleeve are connected directly to the more noble reinforcing steel. A significant amount of copper grounding may also exist around the building foundation wall. This coupling must be overcome first so that adequate polarization is realized on the most anodic material. Hence, 100 mV of polarization is not always enough to ensure the structure is fully polarized, especially if the mixed native potential that is measured on the pipe is extremely depressed. Therefore the use of the 100 mV polarization criterion should be limited to piping that is electrically isolated or piping systems where the effect from dissimilar metal couplings, such as carbon steel and copper grounding, is minimal.

As stated in Section 3.0, space limitations may preclude installation of anodes in certain areas of the plant and shielding effects may limit the distribution of protective current, especially if the piping is installed beneath a concrete foundation slab, such as beneath a turbine building slab. Therefore it may not be possible to fully cathodically protect the buried piping at all locations in the plant using the above stated criteria. Nevertheless, the reduction in corrosion rate can be quite significant, even when a reduced level of cathodic polarization is realized on the pipe surface.

4.10.2 Special Conditions Regarding CP Criteria

When active MIC has been identified or is probable (caused by acid producing or sulfate-reducing bacteria), the CP criteria listed in Section 4.10.1 for carbon steel pipe and gray or ductile iron pipe may not be sufficient. Under some conditions, a polarized potential of -950 mV (CSE) or more negative, or as much as 300 mV of cathodic polarization may be required for adequate cathodic protection.

At elevated temperatures (>40ºC [104ºF]), the criteria listed in Section 4.10.1 for carbon steel and gray or ductile iron pipe may not be sufficient. At potentials greater than 60ºC (140ºF), a polarized potential of -950 mV (CSE) or more negative may be required for adequate cathodic protection.

For aluminum piping a minimum of 100 mV of cathodic polarization should be achieved. Either the formation or decay method for determining the level of polarization may be used. To prevent the build-up of alkali on the aluminum surface and prevent corrosion from high-pH conditions, excessive voltages exceeding a polarized potential of -1200 mV (CSE) should be avoided.

For copper piping a minimum of 100 mV of cathodic polarization should be achieved. Either the formation or decay method for determining the level of polarization may be used.

For stainless steel piping a minimum of 100 mV of cathodic polarization should be achieved. Either the formation or decay method for determining the level of polarization may be used. A polarized potential of -450 mV (CSE) or more negative in neutral or alkaline soils may also be used for stainless steel piping. In acidic conditions, the protected potential should be determined by testing.

Amphoteric materials, such as aluminum and lead, could be damaged by the high alkalinity created by CP. Therefore these metals should be electrically isolated and protected with a separate system.

For PCCP lines a minimum of 100 mV of cathodic polarization should be achieved. Either the formation or decay method for determining the level of polarization may be used. Polarized potentials more negative than -1000 mV (CSE) should be avoided to prevent hydrogen generation and possible embrittlement of the high-strength prestressing wire. For this reason galvanic or sacrificial anodes are commonly used for cathodic protection of PCCP, rather than impressed current systems. PCCP manufactured with Class IV prestressing wire is more susceptible to over protection and hydrogen embrittlement and special precautions must be used when applying CP to these structures.

4.10.3 Over Protection

Under certain conditions, excessive amounts of CP current to a coated pipeline may damage the coating. This process is called cathodic disbondment. Cathodic protection reactions result in the formation of hydroxyl ions (OH^-) on the pipeline surface, which increases the pH. If the polarized potential is sufficiently negative, hydrogen can evolve in the form of gas on the surface of the structure being protected (the cathode). Although the amount of hydrogen evolution is considered to be small, the increase in pH at the pipeline/coating interface can result in cathodic disbondment of the protective coating. Nevertheless a high level of alkalinity at a flaw in the pipeline coating is not necessarily an undesirable condition, as this is an indicator that the protective hydroxyl ion film has formed at the cathode surface.

The Code of Federal Regulations (Parts 192 and 195) for the transportation of natural gas and hazardous liquids by pipeline, warns that care should be exercised to avoid over protection, which can result in coating damage and may promote hydrogen damage of susceptible steels. The potential above which coating damage can occur is a function of many variables, including soil composition and moisture content, temperature, coating type, quality of the coating application, and the presence of microbes. In general tape wrap coatings are considered to be more susceptible to cathodic disbondment. The International Organization for Standardization (ISO) in Standard 15589-1 has stated that "to prevent damage to the coating, the limiting critical potential should not be more negative than -1200 mV (CSE), to avoid the detrimental effects of hydrogen production and/or a high pH at the metal surface." This maximum voltage (Instant-Off potential) is recognized as a guideline for over protection in the pipeline industry.

5
DESIGN AND INSTALLATION OF CP SYSTEMS

The following factors should always be analyzed when designing either type of cathodic protection system:

- **Current Requirement**. This includes a determination of the total current requirement for cathodic protection from either the results of actual current requirement testing or by multiplying a design current density by the surface area of the structure or yard area.
- **Anode-to-earth Resistance**. This includes a determination of the soil resistivity, anode-to-earth resistance of a single anode, anode-to-earth resistance of multiple anodes, and the effects of anode configuration, anode dimension (length, width and/or diameter) and anode spacing.
- **Anode Weight.** This is important when using either galvanic or impressed current anodes for determining the anode consumption. Magnesium is consumed at a typical rate of 17 pounds (7.7 kg) per ampere year (lb/A-yr.) and Zinc at a rate of 26 lb/A-yr. (11.8 kg/A-yr). One lb/A-yr. for high silicon cast iron anodes and 2.5 lbs/A-yr (1.1 kg/A-yr) for graphite are typical consumption rates for impressed current anodes. Anode weight is typically not a concern when using MMO titanium based anodes, as the oxidation reaction occurs primarily at the precious metal oxide interface.
- **Anode Backfill.** This is usually justified by increased anode efficiency and reduced consumption. The backfill also lowers the anode-to-soil resistance. For soil applications, a bentonite/gypsum/sodium sulfate backfill is used as a backfill to encapsulate galvanic anodes. A metallurgical grade coke breeze or petroleum grade coke backfill are typically used as a backfill around impressed current anodes.
- **Seasonal Variations.** The effect of seasonal variations in electrolyte resistivity from variations in soil conductivity due to moisture content should be considered. Ideally anodes should be installed in low resistivity soils beneath the water table.
- **Cable Resistance.** For impressed current systems, the cable resistance should be determined to minimize voltage drop.
- **Design Margin.** Typically a minimum 20% margin should be included in the CP system design. Redundant anodes, junction box terminals, shunt terminals, anode mass, current availability, voltage availability, conductor size, conductor paths (looped conductors) and other measures should be taken account when designing a CP system.

Detailed information regarding the design of an impressed current cathodic protection system or galvanic anode cathodic protection system can be found in Peabody's *Control of Pipeline Corrosion*, 2nd Edition, NACE International Item No. 37571. A companion CD-ROM with actual working spreadsheets for the various CP design equations for both impressed current and galvanic anode systems is available from NACE with this publication.

EPRI publication 1025252 provides guidelines for CP design specifications[15]. This report covers the requirements for the design, installation, monitoring, maintenance and modification or upgrading cathodic protection systems at nuclear power plants. Although the primary focus of the report is for buried piping, the guidance presented is also applicable to other equipment and facilities at nuclear generating stations.

5.1 Current Requirement for Cathodic Protection

The total current required for cathodic protection is the first step in the CP design process. The total current should be determined using a design current density for the structure, area being protected or from the results of actual current requirement test data. Typically a current density ranging between 0.1 and 1.0 mA/ft^2 (1-20 mA/m^2) is sufficient for CP of the exposed steel surface area of an electrically isolated coated steel pipeline in soil. Table 5-1 provides a summary of the approximate total current density range for CP of a coated or wrapped steel pipeline in soil as a function of soil resistivity.

Table 5-1
Approximate Current Requirements for Cathodic Protection of Coated or Wrapped Steel in Soil

(Source: NACE Corrosion Engineer's Reference Book, 3rd Edition)

Soil Resistivity (Ohm-cm)	Current Density (mA/m^2)	Current Density (mA/ft^2)
50 - 500	1 - 2	0.1 – 0.2
500 - 1,500	0.5 – 1.0	0.05 – 0.1
1,500 – 4,000	0.1 – 0.5	0.01 – 0.05

However the piping in nuclear power plants is grounded and therefore much of the current will flow to other structures not intended for CP, such as the copper grounding. As stated in Section 2.4 the current density required to polarize the copper to an adequate potential necessary to protect a ferrous structure may be 10 to 20 times as high, on a per unit basis. When planning a CP system design for buried nuclear piping, sufficient current should be available to provide at least 2 mA/ft^2 (21.5 mA/m^2) of yard area for complex piping configurations. This will provide a conservative estimate for CP of the buried piping in a congested area with extensive grounding. Modeling software may be used to analyze and plot expected current densities, structure-to-soil potentials and electro-magnetic fields. The software can also be used to optimize anode placement, review various design scenarios and predict performance of both galvanic and impressed current cathodic protection systems.

Current requirement testing can provide a more reasonable estimate of the total current required for cathodic protection of the buried piping at a nuclear power plant. During a current requirement test, direct current is forced to flow from a temporary anode source to the pipeline section being studied using a portable test rectifier or other DC power supply. Prior to the current requirement testing native (as-found) structure-to-soil potentials are measured along the structure. The rectifier is then energized and the structure is allowed to polarize. The output of the test rectifier is adjusted and potential measurements are obtained along the section of pipe

[15] EPRI Publication 1025252, "Cathodic Protection Design Specification Guidelines", Technical Update, December, 2012.

being tested, so the level of polarization as a function of applied current is determined. Extrapolations are then made regarding current distribution and the amount of cathodic protection needed. Table 5-2 provides an example of data from two current requirement tests on a section of pipe. Both tests would indicate that less than 10 Amps of current is required for cathodic protection of this line. Therefore the anodes that are selected for the anode groundbed should have a total current rating that is equivalent to or greater than this value.

Table 5-2
Example of Current Requirement Test Data

Nuclear Power Station										
Current Requirement Test (CRT) Data										
Structure:										
Date:										
		Structure-to-Soil Potential (-mV)				Current (Amps) to meet -850 mV CP Criterion	Structure-to-Soil Potential (-mV)			Current (Amps) to meet -850 mV CP Criterion
			CRT #1 (46V/5.0A)				CRT #2 (64V/3.6A)			
No	Half Cell Location	Native	On	Off	Polarization		On	Off	Polarization	
1	East end of line at riser	384	1603	840	456	5.1	2258	1020	636	3.0
2	Access Vault	341	1696	1070	729	4.0	3404	1600	1259	N/A
4	20 ft west	378	3868	1200	822	3.5	707	498	120	6.2
5	40 ft west	270	2691	1050	780	4.0	488	339	69	9.1
6	60 ft west	347	823	579	232	7.3	3381	1050	703	2.9
7	80 ft west	395	830	590	195	7.2	3018	980	585	3.2
8	100 ft west at Bldg.	415	-800	622	207	6.8	1200	790	375	3.9

For current requirement testing a temporary anode source is needed to discharge current into the electrolyte and onto the structure being protected. Unfortunately, because of the common grounding practice, it is difficult to find isolated structures at nuclear power plants that can be used as temporary anodes. Pipe bollards, which provide vehicle protection for above ground equipment, are typically isolated from the buried pipes and may serve as temporary anodes. However the buried section of the pipe bollard may not be of sufficient depth to accurately simulate current distribution from a permanently installed system. The steel casing of groundwater monitoring wells may also serve as a temporary test anode if the steel casing is of sufficient length. Temporary anodes for current requirement tests may consist of isolated buried metallic structures or metal rods that are driven into the soil. Installing test anodes in the soil at a depth that is similar to or greater than the buried pipe receiving cathodic protection, provides the best simulation of current distribution for a permanently installed system. Test anodes may consist of a section of small diameter pipe with a lead wire attached that is installed vertically in a hole that is sufficiently deep and remote from the buried pipe. Alternately, test anodes may

consist of one or two impressed current anodes that are installed permanently in a vertical hole with coke breeze as the backfill material. These test anodes can then be used at a later date as one of the permanent anodes for the CP system.

Reliability of current requirement testing may be improved with corrosion monitoring test stations. Current requirement tests as described above do not give more than a reasonably close approximation of current required for cathodic protection. Variations in the current demand will be determined by factors such as the anode bed resistance, anode location with respect to the pipeline, polarization effects, amount of piping that is protected by each installation and the overlap of current from adjacent systems. Such variables can provide appreciable differences between survey results and the actual performance of a permanently installed system. Practical experience from similar piping configurations is most valuable when developing a final design for CP at a nuclear power plant.

5.2 Basic Design Procedure for Impressed Current System

For the design of impressed current systems, three steps are taken:

- Total current determination
- Total resistance determination
- Voltage and rectifier determination

5.2.1 Total Current Determination

The total current required for cathodic protection is determined from the actual current requirement measurements or by multiplying a typical current density by the surface area of the structure to be protected.

5.2.2 Total Resistance Determination

The next step in the design of impressed current systems is the determination of the total circuit resistance. This value depends on many factors. In most systems, the resistance of a group of anodes (anode bed) is the controlling factor in the total circuit resistance and is the factor most easily controlled by increasing the number of anodes used. The anode bed resistance is primarily a function of soil resistivity. The total number of anodes to be used is balanced against the power required and the rectifier rating, which is determined by the current and voltage requirements of the system. An anode bed resistance of less than 2 ohms is highly desirable. When more than one anode is used in parallel to reduce circuit resistance, the adjusting factor must be used to determine the total anode bed resistance.

The resistance of a single vertical anode-to-earth (anode backfill) can be calculated by using Dwight's equation as follows:

$$R_v = \frac{0.00521\rho}{L}(2.3\log\frac{8L}{d} - 1) \qquad \textbf{Eq. 5-1}$$

Where:

R*v*=resistance of vertical anode to earth in (ohms)
ρ = resistivity of earth in (ohm-cm)

L = length of anode column in (feet)
d = diameter of anode in (feet)

The resistance of several anodes in parallel can be calculated by the following equation:

$$R_v = [\frac{0.00521\rho}{NL}(2.3\log\frac{8L}{d} - 1 + \frac{2L}{S}(2.3\log 0.656N)] \quad \textbf{Eq. 5-2}$$

Where:

R*v*=resistance of vertical anode to earth in (ohms)
ρ = resistivity of earth in (ohm-cm)
L = length of anode column in (feet)
d = diameter of anode in (feet)
N = number of anodes in parallel
S = anode spacing in (feet)

Extending this analysis, assume that a groundbed installation site has been selected where the effective soil resistivity for design purposes has been determined to be 8,000 ohm-cm. Assume that the groundbed will consist of 10 vertical anodes with a carbonaceous backfill. Assume the coke breeze backfill dimensions for one anode well will be 8" diameter x 20 ft. in length. Assume the anode spacing will be 25 ft. and the anode bed will be 200 ft. remote from the structure. Assume that a No. 4 AWG copper conductor will be used as the positive header cable. Assume that the coating resistance to earth is negligible. The total resistance can be calculated as follows:

R*v* = 1.56 Ω
Rcable = 0.05 Ω
Rtotal = 1.61 Ω **Eq. 5-3**

5.2.3 Rectifier Size Determination

Using the total circuit resistance and the output current required for the circuit, the appropriate voltage for the rectifier is then calculated using Ohm's law:

E = I R **Eq. 5-4**

where:

E = required voltage
I = required current for cathodic protection
R = total circuit resistance

In practice, the current and voltage required may be higher than those anticipated values due to the deterioration of coatings on the system, additions to the system, aging of the power supplies, and inaccuracies in the system design. A back voltage which exists between the anodes and pipeline in opposition to the applied voltage is also factored into the design. For anode beds with carbonaceous backfill, this will normally be in the order of 2V (back emf). Rectifiers are normally selected with a capacity in excess of the required rating in order to have additional margins. The margin on the voltage is up to 100% with the maximum output voltage rating of the rectifiers limited to 120V. The margin used on the current rating is up to 100%. Usually, rectifiers are limited in their ratings to 100A. If necessary, additional rectifiers are used rather than larger capacity rectifiers. Using the above example where 10 Amps of current is required for

the pipeline (as determined through current requirement testing) and assuming a total circuit resistance of 1.61 Ohms, the rectifier voltage can be calculated as follows:

E = (10 A x 1.61 Ω) + 2 V (Back emf) = 18.1 V **Eq. 5-5**

Therefore consider using a rectifier with a DC output rating of 24V/14A.

5.3 Basic Design Procedure for Galvanic Anode Systems

For galvanic anode systems, the total current required needs to be determined either from the results of actual current requirement testing or by multiplying a design current density by the surface area of the structure. Then the output of the galvanic anode or anodes is determined. Soil resistivity is an important factor in the design of a CP system.

The number of anodes is then determined by dividing the total current required by the output per anode. The expected anode life is estimated based upon the practical deterioration rate for the selected anode material. Magnesium is consumed at a typical rate of 17 pounds (7.7 kg) per ampere year (lb/A-yr.). As the actual design is an iterative process, such factors as anode size or material may be adjusted in order to optimize the system being designed.

For a single 17-lb high potential magnesium anode (having backfill dimensions of 5” x 55”) the expected current can be calculated using the driving potential of the anode (-1.7V), assumed polarized potential of the cathode (-0.85V), and the calculated resistance (using Dwight’s equation) for a vertical anode in 20,000 ohm-cm soil.

Driving Potential = 1.7 - 0.85 = 0.85 V

Rv = 39.5 Ω

Current = 0.85/39.5 = 0.021 A (or 21 mA)

For magnesium, anode life may be determined by the following expression:

$$Life(years) = \frac{0.116 \times Anode\,Weight\,(lbs) \times Utilization\,Factor}{Design\,Current\,(Amperes)} \qquad \textbf{Eq. 5-6}$$

As an example, assume that a 17-lb magnesium anode is producing 0.021 Amps at 50% efficiency with a utilization factor of 0.85, the expected life would be:

$$Magnesium\,Life\,(years) = \frac{0.116 \times 17 \times 0.50 \times 0.85}{0.021} = 39.9\ years \qquad \textbf{Eq. 5-7}$$

6
PERIODIC TESTING AND INSPECTION

6.1 General

The purpose of a monitoring and maintenance program is to ensure the effectiveness of the CP system throughout the life of the structure. Electrical measurements and inspection are necessary to ensure protection levels have been established in accordance with applicable CP criteria and that each part of the CP system is operating properly. Conditions that effect protection levels are subject to change. Periodic measurements and inspections are necessary to detect changes in the CP system.

Subsequent to the commissioning of the system, periodic inspection of the CP system should be performed in accordance with approved procedures. These procedures should be subject to review to reflect new operating experiences, additions to the system and/or new technology. Records for both operation and maintenance of the CP system should be maintained and trending of data is necessary to observe changes in current delivery, operating voltage, anode bed resistance and structure-to-soil potential. Remote monitoring of the rectifier DC output may be used to help facilitate this requirement. Manual records may be acceptable for some systems, but for larger volumes of data, computer based systems are preferred. Procedures for maintaining the accuracy of measuring equipment and instrumentation are necessary.

Care should be exercised in determining the location, number and type of electrical measurements used to determine adequacy of CP. When practical and determined necessary, a close interval potential survey (CIS) should be performed over the piping to provide base line data, access the effectiveness of the CP system, locate areas of inadequate protection, identify areas likely to be adversely affected by construction, stray current activity or other unusual conditions, and select areas to be monitored more closely.

6.2 Frequency of Inspection

All rectifiers operating impressed current systems should be checked at two (2) month intervals. Longer or shorter intervals may be appropriate. Evidence of proper functioning may include measurement of the rectifier DC output voltage and current, a signal (such as a status lamp) indicating normal operation of the rectifier, or satisfactory CP levels on the piping.

All impressed current CP systems should be inspected annually as part of a preventative maintenance program to minimize in-service failure. Longer or shorter intervals may be appropriate. Rectifier inspections may include a check for electrical malfunctions, safety ground connections, meter accuracy, efficiency and circuit resistance. The annual inspection should include measurement of the polarized (instant-off) structure-to-soil potential at test stations and other monitoring sites using portable and/or permanently installed reference electrodes, anode currents at junction boxes, and rectifier DC output voltage and current readings. Ideally annual inspections should be conducted at the same time of year so as to provide data that is consistent

with the environmental conditions, such that adequate cathodic protection is evident throughout the entire year.

All galvanic anode CP systems should be inspected annually as part of a preventative maintenance program to minimize in-service failures. Longer or shorter intervals may be appropriate. Where appropriate, the inspection should include measurement of the structure-to-soil potential at test stations, measurement of the galvanic anode current and where appropriate verification that isolation joints and DC de-coupling devices when installed are effective.

On a 3-year frequency consider performing a close interval survey (CIS) over all critical piping systems. Longer or shorter intervals may be appropriate. The CIS should consist of a current interrupted survey using GPS synchronized current interrupters in all effected rectifiers. Depending on the sections of pipeline being surveyed and the number of rectifiers at the plant, a rectifier influence survey may be needed to determine which rectifiers require interruption. The CIS should include “on” and polarized “instant-off” structure-to-soil potentials.

6.3 Test Equipment

The test equipment used for obtaining each electrical value should be of an appropriate type as indicated in the test procedures. Meters and related test equipment should be maintained in good operating condition and checked for accuracy on an annual basis.

6.4 External Corrosion Control Records

External corrosion control records should be maintained in a clear, concise and workable manner. Data should be retained that is pertinent to the design, operation, maintenance and effectiveness of the CP system. All data relative to corrosion leaks, breaks, corrosion damage, root-cause analysis and pipe replacements should be maintained. The pipe condition and external coating condition observed when a pipe is exposed should be documented. Information relative to the design of the CP system should be maintained such as location and date of placement, number, type, size, depth, backfill and spacing of anodes. Records regarding cable size, placement and type of insulation should be maintained. The location and type of test station should be documented. If reference electrodes are used the type, location and date of installation should be documented. Specifications, wiring diagrams and operating and maintenance manuals for rectifiers, interrupters and remote monitoring equipment if installed should be maintained by the system engineer. Copies of the rectifier operating and maintenance manual and circuit diagram should be placed in each rectifier enclosure using a water tight envelope.

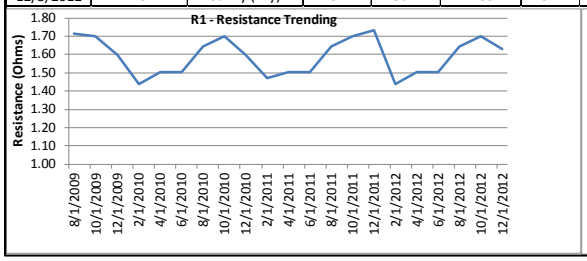
6.5 Trending

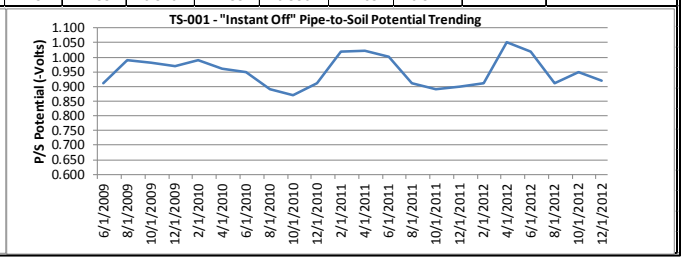
Trending of data is necessary to observe changes in CP system performance. The System Engineer should collect, analyze and manage the data in such fashion to facilitate predictive monitoring and maintenance. Predictive analyses can identify pending problems and is a useful tool for planning cathodic protection system upgrades and/or replacements. The most suitable method for trending data includes the development of computerized spread sheets that allow monitoring of rectifier operating current and voltage, anode bed resistance and structure-to-soil potential. The date, time, ambient temperature, weather conditions and the technician or engineer taking the measurements should be entered with each set of readings. When the data is presented in a graphical format, observations can be made regarding CP system performance, anode consumption and changes as a result of seasonal variations or other environmental conditions.

Table 6-1 provides an example of a system log with data trending of anode groundbed resistance and structure-to-soil potential.

Table 6-1
Example of Data Trending

			Rectifier DC Output			Tap Settings		Structure-to-Soil Potential (Volts-CSE)							
Date	Temperature (°F)	Whether Conditions	R-1 (Volts)	R-1 (Amps)	Resistance (Ohms)	Course	Fine	TS-001 On (-Volts)	TS-001 Off (-Volts)	TS-002 On (-Volts)	TS-002 Off (-Volts)	TS-003 On (-Volts)	TS-003 Off (-Volts)	Technician	Comments
6/8/2009	71	Overcast (Rain)	45.3	30.1	1.50	C-1	F-5	1.050	0.910	1.050	0.900	1.050	0.915	BLM	
8/3/2009	85	Sunny (Dry)	50.2	29.3	1.71	C-1	F-5	1.100	0.990	1.100	0.980	1.100	0.990	BLM	
10/5/2009	66	Sunny (Dry)	48.9	28.8	1.70	C-1	F-5	1.103	0.980	1.103	0.970	1.103	0.985	BLM	
12/7/2009	45	Sunny (Dry)	48.1	30.1	1.60	C-1	F-5	1.150	0.970	1.150	0.970	1.150	0.970	BLM	
2/8/2010	39	Overcast (Rain)	44.7	31.1	1.44	C-1	F-5	1.100	0.989	1.100	0.989	1.100	0.989	BLM	
4/3/2010	50	Overcast (Rain)	45.6	30.3	1.50	C-1	F-5	1.150	0.960	1.150	0.955	1.150	0.960	MTC	
6/7/2010	75	Sunny (Dry)	45.3	30.1	1.50	C-1	F-5	1.090	0.950	1.090	0.950	1.090	0.950	MTC	
8/2/2010	90	Sunny (Dry)	48.2	29.3	1.65	C-1	F-5	1.155	0.890	1.155	0.880	1.155	0.895	MTC	
10/4/2010	68	Sunny (Dry)	48.9	28.8	1.70	C-1	F-5	1.110	0.870	1.110	0.875	1.120	0.880	MTC	
12/6/2010	49	Overcast (Rain)	48.1	30.1	1.60	C-1	F-5	1.250	0.910	1.250	0.910	1.250	0.910	MTC	
2/7/2011	42	Overcast (Rain)	45.7	31.1	1.47	C-1	F-5	1.150	1.020	1.150	1.020	1.150	1.020	MTC	
4/4/2011	55	Overcast (Rain)	45.6	30.3	1.50	C-1	F-5	1.103	1.022	1.103	1.022	1.103	1.022	MTC	
6/6/2011	71	Overcast (Rain)	45.3	30.1	1.50	C-1	F-5	1.150	1.003	1.150	1.003	1.150	1.005	MTC	
8/1/2011	87	Sunny (Dry)	48.2	29.3	1.65	C-1	F-5	1.100	0.910	1.100	0.910	1.100	0.910	MTC	
10/3/2011	69	Sunny (Dry)	48.9	28.8	1.70	C-1	F-5	1.150	0.890	1.150	0.890	1.152	0.890	MTC	
12/3/2011	49	Sunny (Dry)	52.1	30.1	1.73	C-1	F-5	1.150	0.900	1.150	0.900	1.150	0.900	MTC	
2/5/2012	39	Sunny (Dry)	44.7	31.1	1.44	C-1	F-5	1.150	0.910	1.150	0.910	1.155	0.910	MTC	
4/6/2012	55	Overcast (Rain)	45.6	30.3	1.50	C-1	F-5	1.190	1.050	1.190	1.050	1.190	1.052	MTC	
6/4/2012	75	Overcast (Rain)	45.3	30.1	1.50	C-1	F-5	1.150	1.020	1.150	1.120	1.150	1.020	MTC	
8/6/2012	88	Sunny (Dry)	48.2	29.3	1.65	C-1	F-5	1.177	0.910	1.177	0.910	1.177	0.912	MTC	
10/1/2012	68	Sunny (Dry)	48.9	28.8	1.70	C-1	F-5	1.150	0.950	1.150	0.950	1.150	0.950	FRV	
12/3/2012	48	Sunny (Dry)	49.1	30.1	1.63	C-1	F-5	1.155	0.920	1.155	0.950	1.165	0.921	FRV	





6.6 Asset Management Strategies

The planner and system engineer should also consider strategies for proactive and/or rational replacement of the CP system. If the system is installed in stages, it should be planned for replacement in stages. If the system is degrading faster in one area than another, funding should be established to replace the degrading components in a proactive and rational manner. Often good key performance indicators (KPIs) allow a qualified engineer to track/trend deterioration and perform last-minute maintenance (e.g. increase voltage, replace defective components and provide repetitive watering of anode beds) before complete failure of the system occurs. The CP systems at many nuclear power stations are in disrepair today because the simple steps required for system upgrade and replacement were not planned, budgeted for and implemented in a rational and timely manner.

7
PREVENTIVE MAINTENANCE PRACTICES

Even though cathodic protection systems typically have a design life of over 20 years, they should be maintained periodically to ensure their effectiveness. If cathodic protection is properly installed and maintained the life cycle cost of the structure is extensively reduced.



Key O&M Cost Point

If the cathodic protection system is properly installed and maintained the life cycle cost of a structure is extensively reduced.

By implementing an effective cathodic protection program, the premature failure of plant piping that causes unplanned or extended outages, foreign substance spills or in the case of nuclear power plants radioactive leaks, the potential damage liabilities are greatly reduced. Environmental cleanup, transportation, and disposing of contaminated soil and other costs connected to a "reportable" leak can result in a substantial expenditure in terms of time and money. Environmental violations can result in fines, penalties and additional oversight. Cathodic protection is essential to maintaining any metallic structure in a corrosive environment at the lowest life cycle cost.



Key Human Performance Point

By implementing an effective cathodic protection program, the premature failure of plant piping that causes unplanned or extended outages, foreign substance spills or in the case of nuclear power plants radioactive leaks, the potential damage liabilities are greatly reduced.

Over time, the consumption of the anodes, changes to the plant configuration, or changes in the geological properties such as moisture content in the soil can result in inadequate cathodic protection. Also changes in the cathodic protection system, such as broken cables and short circuit conditions, can result in decreased current output to the structure thus reducing the effectiveness of the CP system. Construction of additional piping systems and/or structures in the vicinity of existing piping systems may interfere with the protective current delivery; thus reducing the effectiveness of CP system.

Maintenance of the CP system may include scheduled maintenance, periodic inspection and replacement and/or adjustment of the system components. Unscheduled maintenance may include troubleshooting and repair of defective items and components.

The system engineer for cathodic protection at a nuclear power plant is responsible for monitoring the system performance, identifying problems and solutions, identifying maintenance to be performed with procedures, and identifying testing to be performed with procedures. Usually the system engineer has a background in mechanical, electrical, chemical, or nuclear engineering. The system engineer should have training in corrosion and corrosion control by cathodic protection. He or she must have good knowledge of the nuclear regulatory requirements, as well as the industry codes and standards. System engineers are part of the plant staff. Additional responsibilities of the system engineer may include:

- Trending of rectifier operating data and CP system performance data
- Maintaining all CP system manuals, design documents, as-built drawings and operating documents
- Preparation and maintenance of the site CP system procedures
- Obtaining appropriate qualifications for site personnel
- Arranging for site access and training of contractors
- Preparing procurement specifications for subcontract services
- Monitoring contract services
- Reviewing contractor reports
- Preparing periodic health reports
- Initiating corrective actions and repairs

The development of an effective CP maintenance program for an impressed current system or galvanic anode system requires a basic understanding of the system and its design features. NACE International has been actively involved in issuing recommended practices (RP), standard practices (SP), test methods and other publications for the maintenance of CP systems and its components for various applications. EPRI has developed various maintenance guides for corrosion control of buried piping systems. These guides should be used as applicable in developing a preventive and predictive maintenance program for the CP system.

7.1 Required Data

The following information is typically required to perform various maintenance activities for the CP system components.

- **CP System Design Documents.** Cathodic protection system design documents, assumptions and calculations.
- **As Built Drawings.** As built drawings showing the CP system layout: location and configuration of the anodes, location of insulating devices if applicable, location and configuration of the test stations, anode junction boxes, structure connections or structures being protected, and the drawings of other structures in the vicinity of the CP system that may shield the distribution of the protective current.

- **CP System Equipment Specifications.** Specifications and data sheets for the anodes, back fill materials, conductors, rectifiers, anode junction boxes, monitoring systems, interrupters, test stations and permanent reference electrodes.
- **Previous Test Data.** The initial and periodic readings taken over time on equipment including operating voltage, current, resistance, structure-to-soil potential measurements at test stations and corrosion coupon data should be obtained to record any trends.
- **Pipeline Coating Materials.** The coating material type should be obtained for the various piping systems receiving cathodic protection.

7.2 Impressed Current System

Impressed current CP systems require monitoring and maintenance to ensure continuous and effective operation.

7.2.1 Requirements from NACE Standards

The following maintenance criteria were extracted from various NACE Standards:

1. All impressed current sources should be checked once every two months. Evidence of proper functioning may include the rectifier current, normal power consumption, a signal indicating normal operation, or satisfactory CP levels on the piping.
2. All impressed current protective facilities should be inspected annually as part of a preventive maintenance program to minimize in-service failure. Inspections may include measurement of the rectifier DC output, anode currents in junction boxes, structure-to-soil potentials at test stations, a check for electrical malfunctions, safety ground connections, rectifier meter accuracy, rectifier efficiency and circuit resistance.
3. A close interval potential survey (CIS) should be conducted to:
   a) Assess the effectiveness of cathodic protection system
   b) Provide baseline operating data
   c) Locate areas of inadequate protection levels
   d) Identify locations likely to be adversely affected by construction activity, stray currents, or other unusual environmental conditions
   e) Select areas to be monitored periodically
4. Whenever the buried piping system is uncovered, visual inspection should be made for evidence of corrosion or coating deterioration.
5. Insulating devices and continuity bonds should be periodically evaluated. This may be performed during the annual survey.
6. Test instruments, reference electrodes should be in good operating condition and should be checked periodically for accuracy.
7. Resistance of anode ground beds to earth should be calculated and if they have changed significantly, the rectifier output should be adjusted for optimum performance of the CP system.

7.2.2 Industry Best Practices

A close-interval survey should be conducted at the following intervals:

- As part of the start-up and commissioning procedure.
- Three years from the last close-interval corrosion survey.

A corrosion survey should be conducted at the following intervals:

- On an annual basis
- Thirty days after major modification to the CP system or the protected structure.
- After any corrosion leak on the protected structure.
- After any inspection or survey which indicates that the current requirement of the last corrosion survey are not valid (low or high potential measurements at the proper current output level).

Rectifiers should be inspected on a bi-monthly basis (once every 2 months). Evidence of proper functioning may include measurement of the rectifier DC output voltage and current, a signal (such as a status lamp) indicating normal operation of the rectifier, or satisfactory CP levels on the piping.

The following are the recommended maintenance intervals:

Table 7-1
Recommended Maintenance Program for Impressed Current System

Task	Frequency
Close Interval Survey (CIS)	• As part of the commissioning and start-up procedure • At 3-year intervals
Corrosion Survey	• 30 days after a major modification to the protected structure or to the cathodic protection system. • Annually • After a leak • After any inspection or survey or inspection that necessitates a corrosion survey
Rectifier Inspection	• At 2 month intervals

7.2.3 Close Interval Survey

A close interval potential survey (CIS) should be conducted to assess the effectiveness of cathodic protection system, provide baseline operating data, locate areas of inadequate protection levels, identify locations likely to be adversely affected by construction, stray currents, or other unusual environmental conditions, and select areas to be monitored periodically. Usually the survey is performed by a vendor that specializes in cathodic protection and indirect survey work.

The lead technician for the CIS should be a NACE certified CP Tester, or equivalent. A close interval survey may consist of the following procedures:

- Pipe location survey.
- Rectifier influence survey to determine which rectifiers need interruption.
- Installation of current interrupters in the DC output of influencing rectifiers.
- Drilling small (½-in. dia.) holes over the piping in areas of asphalt and concrete for placement of portable reference electrodes. Install sealant in holes after the survey is complete.
- Placement of data-loggers at anticipated daily CIS midpoints. Data loggers should be programmed to record the pipe-to-soil potential throughout the duration of daily CIS activities. The results are used to confirm interruption synchronization, monitor for rectifier or AC power problems, and monitor for possible dynamic stray current activity.
- Measurement of GPS coordinates over piping at fences, road crossings, test stations, building entrance points, directional changes, elevation changes, access points and other above ground appurtenances.
- Graphical representation of the close interval survey data. Alignment and overlay with previous survey data, if available.
- Final report to include a description of the test procedures, rectifier DC output data, interruption cycle, interrupter sites, data logger results, CIS survey data, test results, and recommendations for future monitoring, upgrades and/or improvements to the CP system performance. The report should be reviewed and approved by a registered professional engineer or person certified by NACE as a Corrosion Specialist or CP Specialist, if their professional activities include suitable experience in external corrosion control for buried piping systems in plant environments.

7.2.4 Corrosion Survey

As with any other electrical system, impressed current cathodic protection systems require periodic inspection, maintenance, and adjustment for satisfactory operation. Typical testing includes annual cathodic protection surveys to determine the effectiveness of the installed cathodic protection systems and whether the effectiveness of the systems is stable or decreasing. The corrosion survey should be performed by a NACE certified CP Tester or equivalent. The annual corrosion survey normally includes the following:

- Recording the rectifier DC output (voltage and current) using the rectifier meters.
- Verifying rectifier meters by measuring the output with portable test instrumentation and recalibrating rectifier meters as required.
- Recording AC input voltage and current.
- Calculating the efficiency of the rectifier (rectifier efficiency is the relationship of the DC power output divided by the AC power input).
- Recording rectifier tap settings.

- Measuring individual anode currents in the anode lead junction boxes.
- Measuring structure-to-soil potential at test stations using a portable reference electrode or the permanent reference electrode if installed. Tester should interrupt all influencing rectifier sources and measure the “On” and “Instant Off” structure-to-soil potential. Note: If more than one rectifier is influencing a piping system, simultaneous interruption of the influencing rectifiers is necessary using GPS synchronized current interrupters.
- Comparing data with expected values (trending) to determine if corrective measures are necessary.
- Adjusting the rectifier DC output if necessary.
- Visual inspection of the system components (rectifiers, test stations, anode wells, anode junction boxes, conduit, wiring, system negative connections, etc.). Cleaning of dirt, debris and insects from rectifier enclosures, test stations and junction boxes. Conduct standard maintenance of the system components as required.
- Final report to include a description of the test procedures, rectifier DC output data, interruption cycle, interrupter sites, anode current shunt data, structure-to-soil potential measurements at test stations, with recommendations for future monitoring, upgrades and/or improvements to the CP system performance. The report should be reviewed and approved by a registered professional engineer or person certified by NACE as a Corrosion Specialist or CP Specialist, if their professional activities include suitable experience in external corrosion control for buried piping systems in plant environments.

7.2.5 Rectifier Inspection

The purpose of the rectifier operational inspection is to determine the serviceability of the rectifier in supplying direct current to the anodes of the impressed current system. The inspection should be thorough enough to ensure dependable operation until the next inspection. The rectifier inspection should be performed at 2 month intervals, but may be accomplished in conjunction with the close-interval-survey, the corrosion survey, or when any inspection or survey indicates that problems with the rectifier may exist.

The rectifier should be inspected to determine that all the components required to supply current to the anodes of the impressed current system are functioning correctly and will be dependable until the next inspection. The inspection may include:

- Visual inspection of all the rectifier components, circuit breakers, and other power components.
- Checking and tightening all accessible connections
- Checking all components for excessive temperature rise
- Measuring the rectifier DC output voltage and current. If there is more than one circuit on a rectifier panel, each circuit’s voltage and current should be measured.
- If the rectifier is equipped with a current monitoring alarm with status lamp, the status lamp should indicate that the direct current output is within a preselected range consistent with normal operation of the CP system.

- On air-cooled units, cabinets and air screens should be cleaned of dust, dirt and insects. Care should be taken when inspecting rectifiers to avoid contact with stinging or biting insects.
- For oil immersed units, the transformer oil should be checked for proper level and clarity. If the oil level is low, additional approved transformer oil should be added following the guidelines of the rectifier manufacturer. If the oil level is cloudy, or has debris in it, the oil should be drained and replaced. Inspect and replace damaged gaskets on the rectifier cabinet as necessary.

As required by the CP system operating procedures, additional structure-to-soil potential measurements may be taken throughout the system as part of the rectifier inspection, to ensure that the potentials are at the desired values. As required, the rectifier output may be increased or decreased by changing the tap settings to achieve the desired level of protection.

7.3 Galvanic Anode System

The galvanic anode system takes advantage of the natural potential difference between dissimilar metals. In this system, the anode material is consumed, or sacrificed in the process, and the anodes must be periodically replaced to maintain continuous protection.

The galvanic anode system consists of the following components:

- Galvanic anode
- Anode bed/backfill
- Interconnecting cable
- Test station

7.3.1 Requirements from NACE Standards

The following inspection and preventive maintenance requirements are extracted from various NACE standards:

- Effectiveness of CP system should be monitored annually.
- When practicable and determined necessary by sound engineering practice, a close-interval-survey may be conducted over the protected piping.
- Insulating devices and continuity bonds should be periodically checked. This may be performed during the annual survey.
- Test instruments and reference electrodes should be in good operating condition and should be checked periodically for accuracy.

7.3.2 Industry Best Practices

Visual inspections should be performed on the system components. Inspection of the cathodic protection system should include the condition of the test stations and lead wires. Buried structures should be inspected whenever possible, i.e., when the structure is being repaired or modified.

Electrical measurements include measurement of the structure-to-soil potential and anode current at test stations. The electrical measurements should be performed at the time of installation and after 6 months of operation. Subsequently, the measurements should be made annually unless a more frequent inspection is warranted.

Electrical measurements should be made as described in Section 6. For consistent interpretation of data, permanent reference electrodes should be installed and used whenever practical. When portable reference electrodes are used, they should be placed in the same locations as in previous tests.

Anode current measurements can be made either by measuring the millivolt drop across a low-resistance shunt that is installed in the anode circuit or by inserting a DC ammeter (capable of measuring milliamps) in the anode- circuit.

Fluctuation in the periodic anode output values can be expected due to seasonal temperature variations. However, with consistent data taking, these fluctuations can be predicted. If the current value should decrease suddenly or should it be zero, then it is indicative that the anode has been totally consumed or it has become disconnected from the circuit.

The recommended maintenance program for a galvanic anode system is shown in Table 7-2. The frequency of the testing is typically yearly, although more frequent measurements provide a better database for trending purposes.

Table 7-2
Recommended Maintenance Program for a Galvanic Anode System

Task	Interval
Close Interval Survey (CIS)	• Thirty days after initial installation • At 3-year intervals
Corrosion Survey	• 30 days after a major modification to the protected structure or to the cathodic protection system • Annually • After a leak • After any inspection or survey that necessitates a corrosion survey

8
TROUBLESHOOTING

Cathodic protection systems are static systems. If they stop working, the failure may not be noticed unless routine surveillance of a structure or component notes a potential problem or until the protected structure fails. A periodic survey is essential to identify problems with cathodic protection systems so corrective actions are taken before a structure is damaged. The impressed current system has more components than the galvanic anode system and these components can and do fail. The major components in an impressed current system are the rectifier, anode bed, structure (system negative) lead or leads, anode lead (header cable) and the structure (piping). The major components in a galvanic anode system are the anode, test station and the structure lead(s). If a routine cathodic protection survey determines adequate cathodic protection does not exist on a protected structure, then troubleshooting must be performed to determine the lack of protection.

8.1 Impressed Current Cathodic Protection Troubleshooting

Troubleshooting an impressed current cathodic protection system may be required if the protective levels (measured structure-to-soil potentials) have dropped or if there is an abrupt change in the rectifier DC output reading. Either of these changes should initiate troubleshooting of the system to determine the cause of the problem. Low or zero output is most often caused by failure of the power supply to the rectifier, failure of the rectifier or failure (breakage) of the anode cables. Output that tails off steadily over time indicates anode groundbed issues. High current output may indicate a short circuit condition or a reduction in the electrolyte resistivity. Whenever there are sudden or substantial changes to the rectifier output, further investigation is usually required to determine the cause of the change. The first step in troubleshooting and repairing the system is to determine which component has failed. Troubleshooting an impressed current system starts at the rectifier. Often the problem can be spotted at this location by physical observation and then verified by additional testing. To start troubleshooting a rectifier one should study the circuit diagram furnished with the manufacturer's operation and maintenance manual. If there is no circuit diagram, it is usually worthwhile to trace out the circuit and develop a diagram as an aid in the troubleshooting process.

8.1.1 Initial Inspection

First, visually check the rectifier for abnormal conditions such as burn marks, heat damaged components, open connections, etc. Next, check the DC output voltage (negative to positive terminals) and the DC current using a clamp-on milliammeter. If a milliammeter cannot be used and if the circuit has a calibrated shunt, then voltage should be measured across an output circuit calibrated shunt with a multimeter set on the mV scale. The current is then determined by use of the following equation:

$$I_{\text{current output}} = V_{\text{voltage drop}} \left(\text{Current}_{\text{shunt rating}} \div \text{Voltage}_{\text{shunt rating}}\right) \qquad \text{Eq. 8-1}$$

where,

$V_{voltage\ drop}$ is the voltage measured across the shunt.

Compare the output current and voltage measurements to previous readings. The readings should be categorized as high, normal, half of normal, low or at zero.

8.1.2 Increase in Structure Surface

The most common reason for low structure-to-soil potential readings with normal rectifier output for non-isolated systems is an increase in the amount of structure protected. Checks should be performed to identify changes to the structure, such as new construction or changes to the piping connected to the structure.

8.1.3 Coatings

Failure of a coating may cause the current requirements to increase. Whenever the current requirements increase considerably, checks should be performed for construction or digging near the protected structure that may have damaged the structure's coating. If no construction or evidence of excavation is found, the rectifier output should be increased and verification should be performed to determine if a proper level of structure-to-soil potential can be obtained.

8.1.4 Outputs (Meters)

Meter error may cause a low output to appear normal or high. It can also cause a normal output to appear low. As a result, the rectifier output should be checked using calibrated meters. If the installed panel meters are out of adjustment, they should be adjusted to obtain proper readings. If the panel meters cannot be adjusted to operate correctly, they should be replaced.

8.1.5 Anode Bed Dry-Out

Long periods without rain can cause anode beds to dry out. The dry soil has a higher resistance and thus for a given DC voltage, a lower rectifier current will result in less protection to the structure causing the potential readings not to meet the protection criteria. Water may also tend to migrate away from the anode (through electro-osmosis) resulting in a higher anode-to-soil resistance. This condition may also result in a reduced level of cathodic protection. To lower the anode-to-earth resistance, water may be added to the groundbed using vent pipes or by other means.

8.1.6 Anode Bed Troubleshooting

Troubleshooting an anode bed can take a substantial amount of resources. Therefore, the system records should be reviewed to determine if sufficient anode material is expected to remain before attempting to locate and repair the anode bed. If troubleshooting is warranted and the failure is gradual, deterioration of one or more anodes is expected. If a cable was broken, then the deterioration should be seen as sudden change in the structure-to-soil potential readings. The following sections provide additional guidance regarding troubleshooting.

8.1.6.1 Gradual Deterioration

If there is sufficient anode material in the anode bed, the first check should be to measure the current of the individual anodes if the system is designed to permit it. Then an anode bed plot should be performed. The data for the plot is collected by connecting the rectifier negative terminal to the positive meter lead and the reference cell to the negative meter lead and taking a reading every 2 feet (0.61 meters) over the entire length of the anode bed. The results should be plotted on a graph to visualize the gradients. The gradient graph should be examined and specific problem(s) should be identified. Failed anodes should be replaced as required. If the graph indicates that an anode lead is broken, excavations may have occurred in the area of anode cable lead. A fault detector and a cable locator can be used to locate the break in the cable and the anode lead cable should be repaired as required.

8.1.6.2 Sudden Deterioration

If there is sufficient anode material in the anode bed and it appears the anodes are not operational, in the area of anode cable lead look for excavations that have occurred. If none are found, a cable fault detector and cable locator can be used to find the location of the break. The signal generator should be connected to the anode lead cable at the rectifier. A low resistance isolated ground should be used for the signal generator. The signal generator is switched on and the anode lead is traced from the rectifier towards the anode bed. Once the anode lead cable fault is found, the cable break is repaired using an approved connector and water tight splice kits.

8.1.7 Polarization

This is a shift in structure-to-soil potential due to current flow. It is a reaction to resistance effects (e.g. formation of a hydrogen film at the pipe surface, changes in the soil at the metal surface, or other factors). Polarization of the anode bed will result is the gradual decrease in current due to the increase in resistance of the CP circuit. The steps in Section 8.1.6.1 should be followed.

8.1.8 Header Cable

Troubleshooting of faults with header cable should be performed similar to the methods for detecting faults with anode bed troubleshooting under sudden deterioration (see Section 8.1.6.2). If this method is unsuccessful in finding the fault, the anode lead header cable should be replaced between the rectifier and the first anode.

8.1.9 Structure Lead

The structure lead runs from the rectifier negative terminal to the structure. To determine if the structure lead is faulted, with the rectifier ac power turned off, the cables to the anode bed and structure should be disconnected and a temporary anode bed should be connected to the positive terminal of the rectifier. The negative terminal of the rectifier should be connected via an insulated cable to a structure isolated from the structure being tested. The rectifier AC power should be turned on for a short period of time. Once the rectifier is turned on, the current meter will indicate that current is flowing or that there is no current.

8.1.9.1 Current Flow

The presence of current for this test configuration is an indication that the permanent structure lead has an open connection. A fault detector signal generator should be connected directly to the structure lead that was connected to the negative lead of the rectifier. A low resistance isolated ground should be used for the signal generator. The signal generator should be turned on and the structure lead should be traced from the rectifier towards the structure. Once the structure lead cable fault is found, the cable and/or structure connection is repaired.

An alternative method for finding the fault location would be to locate the first connection to the structure and excavate it. Using a continuity check circuit, the continuity should be checked back to the rectifier. If a break is not found, a fault detector signal generator should be connected directly to the structure lead that was connected to the structure. A low resistance isolated ground should be used for the signal generator. The signal generator should be turned on and the structure lead should be traced from the structure towards the rectifier. Once the structure lead cable fault is found, the cable and/or structure connection is repaired.

If the fault is not found, the structure cable lead should be replaced.

8.1.9.2 No Current Flow

If there is no current, the temporary anode bed is insufficient for the test and the anode bed needs to be increased in size.

8.1.10 Loss of Rectifier Diode

Half the normal voltage indicates a problem with the loss of a diode/selenium plate or a problem with the ac input. If the problem is with AC input, Section 8.1.11 should be used for troubleshooting. If the problem is with the stacks (silicon diode/selenium plate), troubleshooting may be performed using the following steps.

Half the normal current output indicates a problem with loss of a diode/selenium plate or a break in the header cable between anodes. Also, it could mean there is a problem with the lead(s) to the anode beds or with the anode beds themselves. To determine if the problem is with the diodes/selenium plate or the anode bed, the voltage across the rectifier output terminals should be measured with a handheld multimeter on the DC Volts scale. If the voltage is normal, troubleshooting should be performed on the anode bed. If the voltage is half-normal, this indicates a problem with the diodes/selenium plates or a bad connection inside the rectifier panel.

With the AC power off, all connections should be checked. The anode and structure leads should be disconnected and the tap bars or shorting wires should be removed. The diodes/selenium plates of the rectifier should be checked with a handheld multimeter on the diode check scale. The resistance between the rectifier negative terminal and both center taps should be checked and the checking should be checked again with leads reversed. The resistance between the rectifier positive terminal and both center taps and leads should be reversed and check should be repeated. Any defective diodes/selenium plates should be replaced.

A good diode has very high resistance in one direction and low resistance in the other direction.

8.1.11 Loss of AC Power

For impressed current systems, the loss of AC feed to the rectifier is a common problem. Troubleshooting should be started by checking the power supply. If the power supply was in the 'on' position, circuit breakers and/or blown fuses should be checked. With the AC power switched 'off', the rectifier fuses and any fusible disconnect should be removed and inspected. Corrosion on fuse caps or fuse holders may interfere with the connection contact and may cause loss of voltage. Using a handheld multimeter with the scale set to ohms, the resistance of each fuse should be measured and any fuse with a measurable resistance should be replaced. Clean the fuse holders and fuses of all corrosion and the fuses should be reinstalled.

With the AC switched 'on' the voltage should be checked with a handheld multimeter on the AC volts scale on both sides of the circuit breaker. If a disconnect exists, the voltage should be measured on the rectifier side of the disconnect. The voltage from the rectifier circuit breaker should be checked using a multimeter. If voltage is not present, this indicates loss of AC power supply to the rectifier; the supply circuit breaker or fuse should be replaced. If voltage is present, the rectifier transformer, connections, breaker, or fuse inside the rectifier panel are faulty.

There are a number of reasons a circuit breaker or a fuse will open in a spurious manner (see Section 8.1.12).

The rectifier transformer windings should be checked by isolating the transformer and checking the DC resistance of the windings with an ohmmeter. The primary winding should have a DC resistance of one to ten ohms and the secondary winding resistance should be less than one ohm. If the transformer doesn't meet these resistance criteria, it should be considered for replacement.

8.1.12 Spurious Circuit Breaker or Fuse Operation

There are a number of reasons a circuit breaker will trip or a fuse will open in what appear to be a spurious manner. If the condition happens occasionally without an obvious reason, non-equipment items that should be considered are:

- Temporary overload due to soil moisture changes,
- Line voltage surges or wrong line voltage connections,
- Intermittent short circuits that can be checked using a soil resistance meter or megger test instrument, and
- Overheating as a result of local environmental conditions

A defective breaker can also cause circuit breakers to trip. This can be checked by looking at the breaker contacts after it has been reset and confirming that they are closed. The breaker should also be checked to assure that the trip value is not too low. If the breaker is defective, it should be replaced.

8.1.13 Voltage Transients

One of the reasons a circuit breaker will trip or a fuse will open in a spurious manner is a line voltage surge. A line voltage surge can be the result of line switching, plant equipment starting/stopping, or lightning strikes. Voltage-recording devices maybe used to capture variations in voltage (surges, swells, or sags). If the recording device shows the AC voltage is out of range, the rectifier transformer tap settings should be adjusted. If voltage surges are

causing the breaker to trip or fuses to blow, surge suppressors may be installed on the input to the CP system equipment.

8.1.14 Excessive Heat

Some heat is normal and expected because rectifiers, SCRs, thyristors, etc. are not 100% efficient in converting alternating current to direct current. This is due to the inherent losses in all electrical elements, which result in heating. Excessive operating temperatures can reduce the expected life of a rectifier. Maintaining proper operating temperatures is essential to achieving satisfactory stack life. With the unit ON, the rectifier panel should be inspected for blocked cooling vents. Most electrical panels are ventilated through screens shielded from direct impact by rain. These screen locations often accumulate dust, dirt, insects or bird nests blocking the flow of cooling air to the panel. With the ac power to the panel off, accumulations that interfere with cooling of the panel or any of its components should be removed. If it is necessary to clean the stacks, a soft brush or cloth should be used, while being careful not to bend or scratch the rectifier stack plates.

If the visual inspection did not determine the cause for the heating, an infrared (IR) inspection of the panel may be performed to look for excessively hot connections or components. Hot connections, besides adding heat to the panel, generally get hotter and eventually fail. Hot connections should be repaired as soon as practical. Hot stacks could be an indication that they are reaching the end of their life or that they need cleaning. Section 8.1.10 provides direction for determining if the stacks are going bad and need to be replaced.

8.1.15 Shorts or Failed Lightning Arrestor

When the rectifier blows a fuse when being energized, troubleshooting starts by looking at the items connected to the cathodic protection system that could cause a short circuit. This includes the lightning arrestor, anode and structure leads and anodes. To troubleshoot the lightning arrestor start by disconnecting it from the circuit. An ohmmeter may be used to check the lightning arrestor for continuity. If continuity exists, the arrestor should be replaced. To troubleshoot for shorts on the anode leads, the continuity of the anode lead should be checked between rectifier negative terminal and the structure to the grounded rectifier case. If continuity is found, visual inspection of the wiring for crossed connections should be performed.

To troubleshoot for shorts on the structure lead, the continuity of the structure lead between rectifier positive terminal and the anodes to the grounded rectifier case should be checked. If continuity is found, visual inspection of the wring should be performed for crossed connections.

The design and “as-built” installation drawings should be checked to see if any of the anodes could be physically touching the structure. If it is possible for the anodes to touch the structure, visual inspection should be performed to ascertain if they are shorted to the structure.

8.1.16 Improperly Sized Fuse

If a fuse blows because it is suspected as being improperly sized, the first step in troubleshooting is to review the records to determine the original fuse design size and the original expected design currents. Also, the rectifier’s rated output should be checked to determine the actual current output before the fuse blew. Based on these records, the appropriate fuse size should be determined.

8.2 Galvanic Anode Troubleshooting

Troubleshooting of galvanic anode cathodic protection systems is a matter of determining if the sacrificial anode has been consumed or if a lead wire connecting the anode to the structure has been broken. The starting point of the troubleshooting is the anode (or anode connection). Galvanic anodes are consumed at a relatively constant rate. As a result, failure of the anode can be predicted by trending measured current versus time.

8.2.1 Common Problems

Common problems with sacrificial anode cathodic protection systems are shorts or failure of dielectrics on isolated protected structures. Sacrificial anodes have a limited ability to supply current due to their limited voltage. When a protected isolated structure is shorted to another structure, the protective current demanded by the combined structures may be much more than the existing anodes can supply. For a galvanic anode cathodic protection system, maintaining electrical isolation of the structures (insulating joints) is essential to the long-term performance of the system. Well-coated structures maintain a high contact resistance with the soil and as a result, have a very low current requirement. Metals that are not well coated and have a low contact resistance with the soil will require more protective current and will deplete the anode on an accelerated basis.

8.2.2 Lead Wire

A sudden reduction in the current output of a galvanic anode indicates that the lead wires may be failing or have failed. Anode leads are often cut by excavations if they are not properly identified before digging begins. This can be controlled by carefully surveying the areas and locating the lead wires before excavation. If the wires are cut during the excavation process, they should be repaired before the excavation is backfilled. Troubleshooting to find the anode lead wire to repair after the excavation has been backfilled is usually not successful and replacement of the failed anode is generally the most economical option.



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Troubleshooting to find the anode lead wire to repair after the excavation has been backfilled is usually not successful and replacement of the failed anode is generally the most economical option.

8.2.3 Anode Consumption

As anode systems approach the end of useful life, the measured potentials and currents begin to change. When the anode current shows a large decline in a routine cathodic protection survey, it is an indication that the anode is reaching the end of its life and that failure is imminent. Potential measurements over the protected structure will begin to show a reduced level of potential in the areas of the failed anodes. A failed anode will also show up as a significant potential drop. When a reduction in potential of a cathodically protected structure is noted, a closer inspection should be performed to determine the extent of the damage to the anode.

A
GLOSSARY

Activation. The changing of a passive surface of a metal to a chemically active state

Active. A state in which a metal tends to corrode with respect to standard hydrogen electrode potential.

Absorption. The surface retention of liquid, gas molecules, atoms, or ions by a solid.

Aeration Cell. An electrolytic cell resulting from differences in dissolved oxygen at two points.

Amphoteric Material. An amphoteric (or amphinprotic) material is one that can display both acidic and basic properties. The term is most commonly applied to the oxides and hydroxides of metals that can form both cations and complex anions. Lead and zinc are examples of amphoteric metals.

Anion. An ion or radical, which is attracted to the anode because of the negative charge.

Anode. An electrode from which, ions and/or electrons migrate towards cathode through the electrolyte and to which, electrons flow through an external conductor.

Anode corrosion efficiency. The ratio of actual to theoretical corrosion based on the total current flow. It is calculated by Faraday's law from the quantity of electricity that has passed.

Anode effect. The effect produced by polarization of the anode in electrolysis e.g., by a gas film.

Anodic inhibitor. A chemical substance that prevents or reduces the rate of the anodic or oxidation reaction by a physical or chemical action.

Anodic reaction. Electrode reaction to produce electrons.

Atmospheric corrosion. The gradual degradation of a material by contact with the contents of the atmosphere, such as oxygen, water vapor, and salts.

Backfill. Material placed in the space around anodes or in the trench around the pipe.

Bimetallic corrosion. (Galvanic Corrosion) Corrosion resulting by contact from dissimilar metal contact.

Biological corrosion. Deterioration of metals as a result of the metabolic activity of microorganisms.

Bituminous coating. Coal tar or asphalt-based coating.

Blister. A raised area on the surface of a coating resulting from the loss of adhesion between the coating and the base metal.

Buried Piping. Pipe that is below grade and in direct contact with soil or concrete

Calcareous coating or deposit. A layer consisting of a mixture of calcium carbonate and magnesium hydroxide deposited on surfaces being cathodically protected because of the increased pH adjacent to the protected surface.

Calomel electrode. A reference electrode used in the measurement of the potentials of other electrodes.

Cathode efficiency. Current efficiency at the cathode.

Cathode. The electrode of an electrolytic cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic corrosion. Corrosion resulting from a cathodic condition of a structure usually caused by the reaction of an amphoteric metal with the alkaline products of electrolysis.

Cathodic disbondment. The destruction of adhesion between a coating and its substrate by products of a cathodic reaction.

Cathodic inhibitor. A chemical substance or mixture that prevents or reduces the rate of the cathodic or reduction reaction by physical or chemical action.

Cathodic polarization. Change of the electrode potential in the active (negative) direction due to current flow.

Cathodic protection. Reduction of corrosion rate by shifting the corrosion potential of the electrode toward a less oxidizing potential by applying an external electromotive force.

Cathodic reaction. Electrode reaction equivalent to a transfer of negative charge from the electronic to the ionic conductor. A cathodic reaction is a reduction process.

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

Cell. See electrochemical cell.

Concentration cell. An electrolytic cell, the electromotive force is caused by a difference in concentration of some component in the electrolyte. This difference leads to the formation of discrete cathode and anode regions.

Concentration polarization. That portion of the polarization of a cell produced by concentration changes resulting from passage of' current through the electrolyte.

Conductivity. The ratio of the electric current density to the electric field in a material. Also called electrical conductivity or specific conductance.

Contact corrosion. A term primarily used in Europe to describe galvanic corrosion between dissimilar metals.

Contact potential. The potential difference at the junction of two dissimilar substances.

Continuity bond. A metallic connection that provides electrical continuity between two metallic structures.

Corrosion. The deterioration of a material, usually a metal, due reaction (oxidation) with its environment.

Corrosion rate. Corrosion effect on a metal per unit of time.

Covalent. The ability to form a bond in which two atoms share electrons.

Current density. The current per unit area.

Deep groundbed. One or more anodes installed vertically at a nominal depth of 15 m (50 ft) or more below the earth's surface in a drilled hole for the purpose of supplying *cathodic protection* for an underground or submerged metallic structure.

Depolarization. A decrease in the polarization of an electrode; the elimination or reduction of polarization by physical or chemical means. Depolarization results in increased corrosion.

Dielectric shield. In a *cathodic protection* system, an electrically nonconductive material, such as a coating, plastic sheet or pipe that is placed between the protected structure and an adjacent unprotected structure to avoid current wastage and to improve current distribution.

Differential aeration cell. An electrolytic cell in which the electromotive force has caused a difference in oxygen concentration at one electrode compared with that at another electrode of the same material.

Disbondment. The destruction of adhesion between a coating and the surface coated.

Electrical isolation. The condition of being electrically separated from other metallic structures.

Electrochemical cell. An electrochemical system consisting of an anode and a cathode in metallic contact and immersed in an electrolyte.

Electrochemical corrosion. Corrosion accompanied by a flow of electrons between cathodic and anodic areas on metallic surfaces.

Electrochemical potential. The potential of an electrode in an electrolyte relative to a reference electrode measured under open circuit conditions.

Electrode polarization. Change of electrode potential with respect to a reference value.

Electrode potential. The potential of an electrode as measured against a reference electrode.

Electrode. A conductor used to establish electrical contact with an electrolytic part of an electrochemical cell

Electrolysis. Production of chemical changes of the electrolyte by the passage of current through an electrochemical cell.

Electrolyte. A chemical substance or mixture, usually liquid, containing ions that migrate in an electric field.

Environment. The surroundings or conditions (physical, chemical, mechanical) in which a material exists.

Faraday's law. (1) The amount of any substance dissolved or deposited in electrolysis is proportional to the total electric charge passed. (2) The amounts of different substances dissolved or deposited by the passage of the same electric charge are proportional to their equivalent weights.

Foreign structure. Any metallic structure that is not an intended part of a cathodic protection system.

Galvanic anode. A metal that, because of its relative position in the galvanic series, provides sacrificial protection to the structure when it is coupled in an electrolyte.

Galvanic cell. A cell in which chemical change is the source of electrical energy.

Galvanic corrosion. Corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

Galvanic current. The electric current that flows between metals or conductive nonmetal in a galvanic couple.

Galvanic series. A list of metals and alloys arranged according to their relative potentials in a given environment.

General corrosion. A form of deterioration that is distributed more or less uniformly over a surface.

Groundbed. A buried anode in the cathodic protection of pipelines or other buried structures.

Half cell. See Reference Electrode.

Holiday. A flaw in the protective coating that exposes the metal surface to the environment.

Impressed current. Direct current supplied by a device employing a power source external to the electrodes of a cathodic protection system.

Industrial atmosphere. An atmosphere in an area of heavy industry with soot, fly ash, and sulfur compounds as the principal constituents.

Inert anode. An anode that is insoluble in an electrolyte. Inert materials, such as graphite, high silicon cast iron and mixed metal oxide coating titanium are used anodes in an impressed current system.

Ion. An atom, or group of atoms, that has gained or lost one or more outer electrons and thus carries an electric charge. Positive ions, or cations, are deficient in outer electrons. Negative ions, or anions, have an excess of outer electrons.

Isolation. See Electrical Isolation.

Limiting current density. The maximum current density that can be used to obtain a desired electrode reaction without undue interference such as from polarization.

Line current. The direct current flowing on a pipeline**.**

Local action. Corrosion due to the action of "local cells," that is, galvanic cells resulting from adjacent non-homogeneous areas on a metal surface exposed to an electrolyte.

Local cell. A galvanic cell resulting from adjacent non-homogeneous areas on a metal surface in an electrolyte.

Metal ion concentration cell. A galvanic cell caused by a difference in metal ion concentration at two locations on the same metal surface.

Noble metal. A metal whose potential is highly positive relative to the hydrogen electrode.

Open-circuit potential. The potential of an electrode measured with respect to a reference electrode or another electrode when no current flows to or from it.

Oxidation. Change in the state of the atoms or ions of an element to a higher positive state by the loss of electrons. An oxidizing agent is an element that can remove electrons to another element.

Oxidation. A corrosion reaction in which the corroded metal forms an oxide

Passivation. The process in metal corrosion by which metals become passive.

Polarization. Polarization is the change of potential of a metal surface resulting from the passage of current directly to or from an electrolyte.

Potential. Voltage difference between two materials. Potential is the driving influence of an electrochemical reaction.

Reduction. A reaction in which there is a decrease in valence resulting from a gain in electrons. Contrast with oxidation.

Reference electrode. A non-polarizing electrode with a known and highly reproducible potential used for potentiometric analyses.

Sacrificial protection. The reduction or prevention of corrosion of a metal in an electrolyte by a galvanic coupling to a more anodic metal.

Shunt. A calibrated precision resistor that allows the current to be determine from a voltage drop measurement using Ohms Law (I=E/R).

Standard electrode potential. The reversible potential for an electrode process when all products and reactions are at unit activity on a scale in which the potential for the standard hydrogen half-cell is zero.

Stray current. The current flowing through paths other than the intended circuit.

Stray current corrosion. The corrosion resulting from direct-current flow through paths other than the intended circuit.

Underground Piping. Pipe that is below grade, but contained within a tunnel or vault such that it is contact with air and is located where access is restricted.

Voids. A term generally applied to paints to describe holidays, holes, and skips in a coating. Also used to describe shrinkage in castings and welds.

B
CATHODIC PROTECTION REFERENCES

B.1 Standards

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4. NACE Standard SP0502-2010, *Pipeline External Corrosion Direct Assessment Methodology, Design, Installation, Operation, and Maintenance of Impressed Current Deep Ground Beds*, (Houston, TX: NACE International).
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20. Code of Federal Regulations, Part 195 – Transportation of Hazardous Liquids by Pipeline: Minimum Federal Safety Standards.

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4. http://www.corrosion-doctors.org
5. http://www.dodcorrosionexchange.org

C
KEY POINTS BY CATEGORY

The primary intent of key points is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these pop outs was selected by the EPRI Project Manager, TAG members, and the consultant that prepared this guide.

The pop outs are organized according to three categories: Operation and Maintenance (O&M) Cost, Technical, and Human Performance. Each category has an identifying icon, as shown below, to draw attention to it when quickly reviewing the guide.



Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.



Key Technical Point

Targets information that will lead to improved equipment reliability.



Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or to ease completion of the task.

The following is a summary of the key points in this report by category. The listing restates each key point and provides reference to its location in the body of the report. By reviewing this listing, users of this guide can determine whether they have taken advantage of key information that the writers of the guide believe would benefit their plants.

C.1 Key O&M Costs Points



Key O&M Cost Point: Section 2 - Corrosion

Consideration of corrosion in the design, material selection, construction, operation and maintenance of structures and components saves billions of dollars in repair, maintenance and replacement costs.



Key O&M Cost Point: Section 3.1.1 – Impressed Current System General Description

Materials such as graphite, high silicon cast iron, platinum, or mixed metal oxide (MMO) are commonly used as impressed current anodes in soil because they have a very low consumption rate.



Key O&M Cost Point: Section 7 – Preventive Maintenance Practices

If the cathodic protection system is properly installed and maintained the life cycle cost of a structure is extensively reduced.



Key O&M Cost Point: Section 8.2.2 – Lead Wire

Troubleshooting to find the anode lead wire to repair after the excavation has been backfilled is usually not successful and replacement of the failed anode is generally the most economical option.

C.2 Key Technical Points



Key Technical Point: Section 2.1 - Electrochemical Corrosion

In order for an electrochemical corrosion cell to form, there must be a difference in potential between two different metallic structures or between one part of a metallic structure and another.



Key Technical Point: Section 2.1 - Electrochemical Corrosion

Every metal immersed in an electrolyte (soil, water, concrete or other electrically conductive material) develops an electrochemical potential due to the free energy of the atoms in the metal.



Key Technical Point: Section 2.1.1 – Basic Electrochemical Reactions

Oxidation is the loss of electrons from an atom or molecule and as a result, energy is released. Reduction is the gain of electrons by atoms and as a result energy is gained. Electrons function as energy carriers.



Key Technical Point: Section 2.2.6 – Microbiologically Influenced Corrosion

Research has shown that a pipe-to-soil potential of at least -950 mV (CSE) is required to mitigate corrosion on pipelines that are susceptible to MIC.



Key Technical Point: Section 2.2.11 – Stray Current Corrosion

Different metals have specific amounts of weight loss when exposed to current discharge. This weight loss is normally measured in pounds (or kilograms) of metal lost due to a current of one amp for a period of one year (one amp-year).



Key Technical Point: Section 2.2.12 – Simultaneous Sources of Corrosion

When corrosion is noted, or when a leak occurs due to corrosion, it is essential that the cause(s) of the corrosion be identified so that the appropriate corrective action can be taken.



Key Technical Point: Section 3 – Cathodic Protection Systems

Because of the significant current requirement and the required service life, the impressed current method is almost always used for cathodic protection of buried piping at nuclear power plants.



Key Technical Point: Section 3.1.7.2 – Deep Anode Beds

The designer of a deep anode system should reference the groundwater protection plan, so as to avoid potential pollution and cross contamination of subsurface aquifers.



Key Technical Point: Section 3.2.1 – Galvanic Anode System, General Description

Because of the relatively small amount of current that is produced and the fact that they typically require the piping to be electrically isolated (fitted with insulating devices) to contain the protective current, galvanic anode systems have limited application at nuclear power plants.



Key Technical Point: Section 3.2.2 – Limitations of Galvanic Anodes

Unless the anodes are used for “hot spot” protection, the galvanic anode method of protection should only be considered for buried pipes that are coated and electrically isolated.



Key Technical Point: Section 3.5 – Permanent Reference Electrodes

Copper sulfate electrodes are the most commonly used reference electrodes. Measurements using other types of reference electrodes are often converted to those of copper sulfate.



Key Technical Point: Section 4.9 – Start-up Testing and Commissioning

Verify correct polarity hook-up of the positive and negative cables at the rectifier DC output terminals. Incorrect termination of the positive and negative cables will result in corrosion of the structure rather than the anode. Double verification is always required for this start-up procedure.

C.3 Key Human Performance Points



Key Human Performance Point: Section 3.1.3 - Rectifiers

Manufacturer's instructions as well as station operating procedures should be followed when handling rectifier equipment. Safety related features should be considered when specifying a rectifier.



Key Human Performance Point: Section 7 – Preventative Maintenance Practices

By implementing an effective cathodic protection program, the premature failure of plant piping that causes unplanned or extended outages, foreign substance spills or in the case of nuclear power plants radioactive leaks, the potential damage liabilities are greatly reduced.

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Cathodic Protection Application and Maintenance Guide

Volume 2: Plant Structures and Equipment

2013 TECHNICAL REPORT

Cathodic Protection Application and Maintenance Guide

Volume 2: Plant Structures and Equipment

3002000596 Volume 2

Final Report, July 2013

EPRI Project Manager
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All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

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PRODUCT DESCRIPTION

Many nuclear power plants are entering into life extension or are applying for license renewal; therefore, it is important for engineers and maintenance staff to focus time and effort on corrosion control systems that are designed to prolong the service life of such plant equipment as tanks, pilings, condensers, heat exchangers, and other structures. For example, by implementing an effective cathodic protection (CP) program, the premature failure of underground diesel fuel oil tanks causing foreign substance spills is greatly reduced. The design and installation of new CP systems may also be required at plants where new infrastructure has been installed, locations where the CP is not adequate, or at plants where CP was not initially used.

This report is provided in two volumes: Volume 1 is for buried piping and Volume 2 is for plant structures and other equipment.

Background

Recent operating experience from nuclear power plants indicates that the degradation of metallic structures in soil, water, and concrete is becoming a maintenance issue. The vast majority of these plants, and particularly those in the United States, are now 30–40 years old. The design life of a typical CP system is approximately 15–25 years. This life expectancy is based on the type of system, operating output, materials that were used, and the environmental conditions that the system is subject to. Many of the older CP systems that were installed when the plant was built are now in need of repair, upgrade, and/or replacement. Some of these systems may not be providing adequate levels of CP to control corrosion of the metallic surfaces, and corrosion-related failures may increase unless appropriate measures are taken.

Objectives

To provide an application and maintenance guide that is specific to cathodic protection of condensers, heat exchangers, reinforced concrete structures, intake structures, steel pilings, underground storage tanks, aboveground storage tanks, and meteorological tower guy anchors. Both impressed current and galvanic anode systems are discussed.

Approach

This guide is divided into sections that deal with cathodic protection systems for various plant structures and equipment units. Each section provides a discussion of the corrosion process for the particular structure or equipment unit, guidelines regarding the selection of a suitable CP system, CP system design details, installation procedures, testing, troubleshooting, and recommendations for monitoring and maintenance.

Results

This guide provides details regarding the selection, application, monitoring and maintenance of CP systems for structures and equipment at nuclear power plants, other than buried piping systems. Guidance for cathodic protection systems has been provided for CP systems that protect condensers and heat exchangers, reinforced concrete structures, intake structures, steel piling,

underground storage tanks, aboveground storage tanks, and meteorological tower guy anchors. The results of this guide will provide the basis for a suitable preventive and predictive maintenance program.

Application, Value, and Use

This guide provides power plant staff with information for establishing an effective application and maintenance program for CP systems and components of various equipment units and structures. The guide outlines the most common failure modes, describes appropriate predictive and preventive maintenance techniques, and provides information on the methods available to optimize service life and minimize maintenance costs through effective preventive maintenance and condition monitoring.

Keywords

Anode
Cathode
Cathodic protection (CP)
Corrosion
Galvanic anode system
Impressed current system

ABSTRACT

Nuclear power plants have numerous structures that must be protected from corrosion. Corrosion of a material is inevitable, but uncontrolled corrosion can increase maintenance costs and, in some instances, cause failure of structures, systems, and components.

Controlling corrosion in nuclear power plants can be accomplished through the proper selection and application of materials, coatings, and cathodic protection. Cathodic protection, when used in conjunction with protective coatings, can reduce the corrosion rate on a metal surface to an acceptable level so that adequate life of the structure can be provided.

With the effort in the nuclear power industry to maximize equipment life, it is important that plant operators understand the importance of corrosion control by cathodic protection in their life extension efforts. Cathodic protection can aid plant personnel in their endeavor to protect and maintain equipment in a safe and reliable manner.

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1
INTRODUCTION

Recent operating experience from nuclear power plants indicates that degradation of metallic structures in soil, water and concrete is becoming a maintenance issue. The vast majority of these plants, and particularly those in the United States, are now 30 to 40 years old. The design life of a typical cathodic protection (CP) system is approximately 15 to 25 years. The life expectancy is based on the type of system, operating output, materials that were used, and the environment conditions that the system is subject to. Many of the older CP systems that were installed when the plant was built are now in need of repair, upgrade and/or replacement. Some of these systems may not be providing adequate levels of CP to control corrosion of the metallic surface(s) and corrosion related failures may increase unless appropriate measures are undertaken. The design and installation of new CP systems may also be required at plants where new infrastructure has been installed, for plant structures that were not previously protected, or at plants where CP was not initially used.

Since most nuclear power plants will be entering into life extension, it is important that engineers and maintenance staff focus time and effort on corrosion control systems that will prolong the service life of plant equipment such as tanks, piling, condensers, heat exchangers and other structures. For example by implementing an effective cathodic protection program, the probability of premature failure of underground diesel fuel oil tanks causing foreign substance release will be greatly reduced. Environmental cleanup, transportation, and disposing of contaminated soil and other costs connected to a "reportable" leak can result in a substantial expenditure in terms of time and money. In addition, some of these structures may require maintenance and inspection per government regulations. Environmental violations can result in fines, penalties and additional oversight. Cathodic protection is essential to maintaining any metallic structure in a corrosive environment at the lowest life cycle cost.



Key O&M Cost Point

Cathodic protection is essential to maintaining any metallic structure in a corrosive environment at the lowest life cycle cost.

1.1 Scope and Purpose of the Guide

In order to plan and implement the appropriate maintenance methods to ensure adequate CP system performance, the type of system (impressed current or galvanic), design, materials selection, installation, testing and commissioning methods must be understood, documented and properly applied. This guide (Volume 2) provides a systematic approach for the design, installation, testing, monitoring and maintenance of CP systems that are used for corrosion control of various structures at nuclear power plants including condensers, heat exchangers, reinforced concrete structures, intake structures, steel piling in soil and water, underground

storage tanks, above ground storage tanks and meteorological (MET) tower guy anchors. Volume 1 of this guide provides guidance specific to cathodic protection of buried piping at nuclear power plants.

Corrosion can cause numerous problems that affect the integrity and capability of various structures, systems or components. For instance, piping systems can degrade and rupture as a result of corrosion. Also, structures such as storage tanks, ships, rail cars, tanker trucks, and nuclear waste facilities, all of which store and/or transport potentially hazardous materials, can be subject to the harmful effects of corrosion. When the structural integrity of equipment is weakened by corrosion, system function, plant operation, personnel safety, public safety and the environment can be threatened.

There are three (3) common methods used to control external corrosion of plant equipment and structures. These methods include proper material selection, protective coatings and cathodic protection:

> *Proper Material Selection* refers to the selection and use of corrosion-resistant materials such as stainless steels, plastics and special alloys to enhance the lifespan of a structure. Some of the most common materials used in construction, such as carbon steel and steel reinforced concrete, can be severely affected by corrosion.
>
> *Coatings* can be any mixture of film-forming materials, which when applied to a surface and cured or dried, provide a thin layer that protects the underlying material from corrosion. Coatings are often applied in conjunction with CP systems to provide the most cost-effective method of protection for buried and immersed metallic structures.
>
> *Cathodic Protection* (CP) consists of methods that use selected materials and the application of direct electrical current to counteract the normal external corrosion of a buried or immersed metallic structure. On new structures, CP can help prevent corrosion from occurring and for existing structures it can effectively reduce the rate of corrosion to an acceptable level.

This guide provides power plant staff with information for establishing an effective maintenance program for CP systems and components. The guide outlines the most common failure modes, describes appropriate predictive and preventive maintenance (PdM/PM) techniques, and provides information on the methods available to optimize service life and minimize maintenance costs through effective preventive maintenance and condition monitoring. Operating history, published literature, and the experience and expertise of numerous users and manufacturers were used in preparing this guide. Data sources include the following:

- Power plant maintenance, operating, and engineering personnel
- Cathodic protection system and equipment manufacturers
- Final License Renewal Interim Staff Guidance LR-ISG-2011-03, Changes to the Generic Aging Lessons Learned (GALL) Report, Revision 2
- National Association of Corrosion Engineers (NACE) International Standard Practices, Test Methods and Publications
- Results of a survey completed by power plant personnel
- EPRI and other technical publications

A glossary of terms relating to corrosion and cathodic protection can be found in Appendix A of this guide. A complete list of standards, test methods and publications for cathodic protection of the structures and equipment units that are included in this guide can be found in Appendix B. A summary of preventive maintenance tasks for cathodic protection is included in Appendix C.

Annual corrosion surveys for cathodic protection system assessment should be performed under the direction of competent persons who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by education and related practical experience, are qualified to engage in the practice of corrosion control on buried or submerged metallic structures. Such persons might be, but are not limited to, registered professional engineers or persons certified by the National Association of Corrosion Engineers (NACE) International as a Corrosion Specialist or CP Specialist, if their professional activities include suitable experience in external corrosion control for structures and equipment in plant environments.

1.2 Key Points

Throughout this guide, key information is summarized in Pop Outs. Pop outs are bold lettered boxes that succinctly restate information covered in detail in the surrounding text, making the key points easier to locate.

The primary intent of a pop out is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these pop outs was selected by the EPRI Project Manager, TAG members and the author of this guide.

The pop outs are organized according to three categories: Operation and Maintenance (O&M) Cost, Technical, and Human Performance. Each category has an identifying icon, as shown below, to draw attention to it when quickly reviewing the guide.

Appendix D contains a listing of all of the key points in each category. The listing restates each key point and provides reference to its location in the body of the report. By reviewing this listing, users of this guide can determine whether they have taken advantage of key information that the author believes would benefit their plants.



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Targets information that will lead to improved equipment reliability.



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Denotes information that requires personnel action or consideration in order to prevent injury or damage or to ease completion of the task.

2
CP OF CONDENSERS AND HEAT EXCHANGERS

Dissimilar metals are commonly used in the design and construction of power plant condensers and heat exchangers. The basic components of these equipment units include the waterbox, tubes, tubesheets, hot well, shell and air-removal equipment. The circulating water, which is always in contact with these components, serves as the electrolyte for corrosion to occur. Cathodic protection (CP) may be used to control erosion-corrosion at the inlet end of the tubes, galvanic corrosion of the tubesheet area, pitting corrosion and general corrosion of the waterbox. CP may be applied using the galvanic or impressed current method. However, because of the high current demand that is required for protection of these units and the relatively short life of galvanic anodes, the impressed current method is usually the preferred approach for cathodic protection of surface condensers and heat exchangers.



Key Technical Point

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2.1 Corrosion Mechanism

Depending on the application, the tubes may consist of copper-alloy, titanium, stainless steel, aluminum bronze or admiralty brass. Commonly used materials for tubesheets include copper alloys, aluminum bronze, carbon steel, stainless steel, titanium or carbon steel clad with stainless steel or titanium. Waterboxes are typically constructed of carbon steel or cast iron, although copper alloys have been frequently used (e.g., Muntz metal) to match the tube material. Coatings are often applied to control corrosion of the tubesheet and waterbox materials and may be used effectively with cathodic protection. However all coatings will degrade over time and corrosion attack can proceed rapidly in the areas of coating failure unless CP is properly applied and maintained.

The primary factors affecting galvanic corrosion in condensers and heat exchangers include the electrochemical characteristics; that is the potential and polarization of the different alloys, the effective area relationships of the different alloys, and the specific characteristics of the cooling water (i.e., conductivity, temperature, oxygen content and velocity). A number of studies have

been conducted to develop a better understanding of the relative influence and the relationship of these factors.[1, 2]

These studies, conducted under simulated condenser flow conditions, have shown that the length of tube involved in a tubesheet/tube galvanic cell can extend beyond 20 ft (6 m) down the tube, depending on the tube alloy and water salinity. Furthermore the use of either titanium or stainless steel tubes with a copper alloy tubesheet could result in significant galvanic corrosion of the tubesheet. A tubesheet that is constructed of Muntz metal and coupled to either stainless steel or titanium, may experience severe dezincification of the tubesheet. The intensity of this galvanic attack will tend to diminish as the conductivity and temperature of the cooling water decreases.



Key Technical Point

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Fresh water coolant at inland power generating facilities is usually recycled through several loops in order to comply with recent environmental constraints. Recirculating water through cooling towers serves to concentrate the water with total dissolved solids and increase its conductivity, thereby increasing the potential for corrosion of structures exposed to this environment. Fresh water cooling can be concentrated to the point where electrical resistivity is on the order of 1,000 ohm-cm (1,000 micro-mhos) or less. Under these conditions, dissimilar metal combinations can experience rapid corrosion unless specific corrosion control measures are implemented. Case histories indicate that failures of tubesheet material can occur within a period of six months of the date of trial operation of a power generating facility.

Similar corrosion patterns can be observed in power plant condensers that use brackish water and seawater as a cooling medium. Seawater electrical resistivities can range from 50 ohm-cm (20,000 micro-mhos) in some environments to as low as 15 ohm-cm (66,667 micro-mhos) in other environments. The exposure to electrochemically-corrosive environments such as recycled fresh water and once-through seawater coupled with exposure to high velocities and increased oxygen levels necessitate the need for implementation of corrosion control measures. Figure 2-1 provides an example of severe galvanic corrosion and impingement attack of a cast iron channel head inside a heat exchanger.

[1] Gehring, George A. Jr., "Galvanic Corrosion in Power Plant Condensers," *Galvanic Corrosion*, *ASTM STP 978*, H. P. Hack, Ed., American Society of Testing materials, Philadelphia, PA 1988.

[2] Gehring, Jr., G. A., Kuester, C. K., Maurer, J. R., "Effective Tube – Length – A Consideration on Galvanic Corrosion of Marine Heat Exchanger Materials", Corrosion 1980, Paper No. 32, NACE International, Houston, TX.



Figure 2-1
Severe Galvanic Corrosion of a Cast Iron Channel Head inside a Heat Exchanger

(Source: PSEG Power, LLC)

2.2 Cathodic Protection

Cathodic protection can be used to mitigate galvanic corrosion of the tubesheet and waterbox, pitting corrosion as well as retard inlet end erosion/corrosion of the tubes. Current densities for CP of the tubesheets and waterboxes typically range from 50-200 mA/ft^2 (~0.5-2.0 A/m^2). The higher current densities can be attributed to the higher conductivity of the electrolyte, temperature, turbulence of the water and the current required to overcome the galvanic corrosion effect. Typically, when designing a CP system, the procedure has been to calculate the total surface area of exposed waterbox and tubesheet area and apply a current density for cathodic protection. The current density required for protection can be determined by field tests on the actual condenser or heat exchanger or can be selected based on prior operating experience. For mitigating galvanic attack of an uncoated ferrous waterbox/tubesheet, the general consensus is that the required current will be 100-200 mA/ft^2 (~1.0-2.0 A/m^2) in higher salinity cooling water. In fresh water, the current density will be lower.

Key Technical Point

Cathodic protection can be used to mitigate galvanic corrosion of the tubesheet and waterbox, as well as retard inlet end erosion/corrosion of the tubes. Current densities for CP of these structures typically range from 50-200 mA/ft2 (~0.5-2.0 A/m2).

If the waterbox is coated, then the designer must take into account the expected coating efficiency of the structure (i.e., to what extent the waterbox/tubesheet area will be exposed to the electrolyte). For example, if the typical exposed area is estimated to be 5% for a 200 m^2 coated area, when using a design current density of 2 A/m^2 the exposed surface may only be 10 m^2 and therefore 20 Amps of current would be required. Once the protective current has been estimated, the type of cathodic protection system (sacrificial anode or impressed current) can be decided. In general, for a surface condenser the sacrificial anode type system becomes impractical at currents

exceeding 50 Amps. It is not uncommon for a typical current demand of an impressed current system to exceed 200 Amps per condenser. EPRI reports 1003088[3] and 1022980[4] provide guidance regarding the general operation and maintenance of condensers and heat exchangers. EPRI report CS-2961[5] and the EPRI Power Plant Reference Series, Volume 11 "Cathodic Protection"[6] provide guidance regarding the design, operation and maintenance of CP systems for steam surface condensers and heat exchangers.



Key Technical Point

In general for a surface condenser the sacrificial anode type system becomes impractical at high levels of current exceeding 50 Amps. It is not uncommon for a typical current demand of an impressed current system to exceed 200 Amps per condenser.

2.2.1 Sacrificial Cathodic Protection

For galvanic systems both magnesium and zinc anodes have been used, although there has been some limited use of sacrificial steel waster plates. The location of the anodes to achieve effective current distribution is usually dictated by symmetry considerations and/or previous experience. The major limitation of using sacrificial anodes in condensers and heat exchangers is the level of protective current that can be realized. The protective current required will depend primarily on the conductivity and temperature of the cooling water, the effective wetted surface area, and the materials of construction. In fresh water the current requirements will be lower and the current output will be limited by the resistivity of the water.

The current output of a galvanic anode is a function of the driving voltage between the anode and the structure and the resistance between the anode and the structure. The current output can be calculated using Ohm's Law (I = E/R). For a sacrificial anode system the voltage between the anode and the structure primarily depends on the anode itself. The driving voltage for zinc and the protected steel is typically 0.25V, whereas the driving potential between magnesium and the protected steel is typically 0.70V. The anode resistance is primarily dependent on the electrolyte resistance, although for coated structures the total effective resistance may become more significant.

Pure zinc is ordinarily an excellent sacrificial anode material because of its high efficiency, which is typically reported to be 90% (efficiency is a measure of the self-consumption of the anode). Although under certain circumstances (e.g., temperatures above 140ºF) and higher

[3] EPRI Report 1003088, "Condenser Application and Maintenance Guide", August 2001, Electric Power Research Institute, Palo Alto, CA.

[4] EPRI Report 1022980, "Guidance for an Effective Heat Exchanger Program", September 2011, Electric Power Research Institute, Palo Alto, CA.

[5] EPRI Topical Report CS-2961, Project 1689-3, "Current Cathodic Protection Practice in Steam Surface Condensers", May 1983, Electric Power Research Institute, Palo Alto, CA.

[6] EPRI Power Plant Reference Series, EL-5036, Volume 11, Project 2334, "Cathodic Protection", 1987, Electric Power Research Institute, Palo Alto, CA.

resistivity electrolytes, zinc has been known to passivate. When passivated, the zinc anode will provide almost no protective current to the structure. Its use should therefore be limited to systems using seawater or brackish water for cooling.

The advantage of magnesium is the greater driving voltage that can be obtained, and therefore the greater current output per unit area of anode surface. However magnesium anodes are disadvantageous in that their efficiency is lower (e.g., 50%) compared to zinc, indicating that half of the anode will deteriorate without providing any useful current. Magnesium anodes, however, have a much higher driving potential than zinc and therefore the current delivery will be significantly greater given the same electrolytic conditions. Magnesium therefore can be used for cathodic protection in higher resistivity (fresh water) environments. Figure 2-2 is a photograph of a galvanic zinc anode that was mounted to the inside lid of a heat exchanger.



Figure 2-2
Galvanic Zinc Anode mounted to the Cover Lid of a Heat Exchanger

(Source: PSEG Power, LLC)

2.2.2 Impressed Current Cathodic Protection

Typically, anodes in impressed current CP systems for condensers and heat exchangers operate at substantially higher voltages and current outputs compared to galvanic anode systems. Anodes are typically probe-type or disc-type anodes consisting of platinized or mixed metal oxide (MMO) coated titanium anodes; although lead alloy and iron alloy anodes were used on some of the earlier systems. The probe-type anode is most commonly used for cathodic protection of condenser waterboxes, although the most troublesome maintenance problem is anode breakage. Figure 2-3 provides a view of an anode connection detail at a waterbox elbow.



Figure 2-3
Anode Connection Detail at a Waterbox Elbow

(Source: PSEG Power, LLC)

Platinized anodes are made using substrates of either titanium or niobium-rod which are covered with a platinum coating. The platinum coating is electroplated to the substrates in thicknesses ranging from 100 to 300 micro-inches, and is consumed at a rate of 816 mg/amp-yr in salt water environments. The recommended current density for both types of probe anodes is between 50 and 300 amp/ft^2 in salt water electrolytes. The MMO rod and disc anodes consist of a precious metal oxide catalyst that is sintered to a Grade 1 titanium substrate. The mixed metal oxide coating is a crystalline, electrically-conductive coating that activates the titanium and enables it to function as an anode. Due to the extremely low consumption rates and dimensional stability, the electrical resistance of MMO anodes remains essentially constant over time. The benefits of using MMO compared to platinum include lower cost, longer life expectancy in salt water and brackish water environments and the fact that the current emitting surface is more resistant to abrasive damage. Figure 2-4 shows a probe-type anode for a condenser waterbox using platinized titanium, niobium or a MMO emitting area. Figure 2-5 shows a disc-type anode for a condenser waterbox using a MMO coated titanium surface.

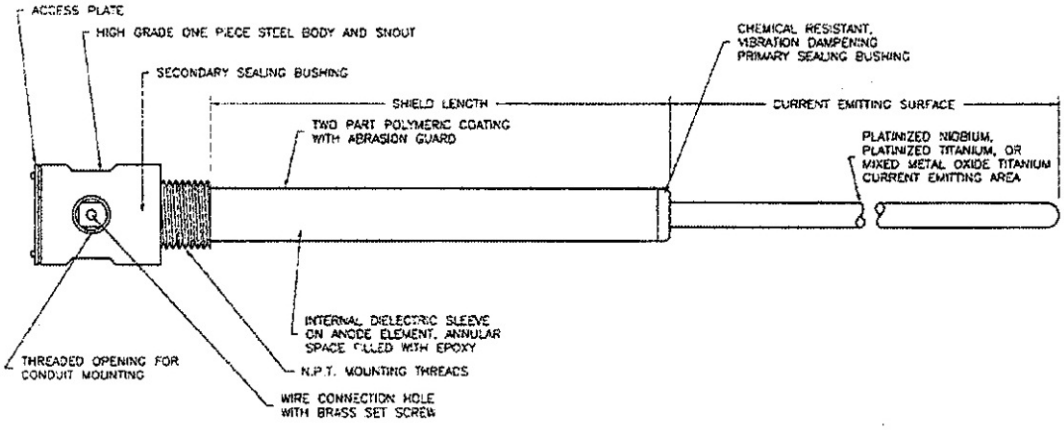


Figure 2-4
Probe-Type Anode

(Source: Norton Corrosion Limited)

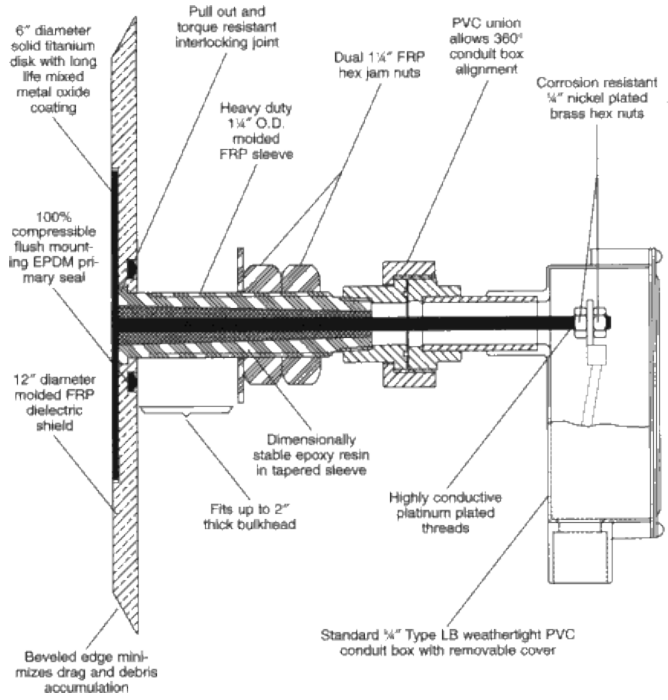


Figure 2-5
Disc-Type Anode

(Source: de Nora Tech, Inc.)

Rectifiers for condenser and heat exchanger impressed current systems use either the manual voltage control or automatic potential control mode. Manual voltage control requires periodic adjustment of the current output to compensate for changes in the cooling water conductivity, temperature, coating resistance and cathodic polarization. Automatic potential control systems are designed to overcome the need for frequent adjustment by station personnel. For these types of rectifiers a signal is generated by comparing the preselected control potential with the measured structure-to-electrolyte potential at a suitable permanent reference electrode location. If the measured potential drops or exceeds the pre-set potential, then a signal is transmitted through a current control card circuit to increase or decrease the current, regardless of the cooling water conditions. These rectifiers may be supplied with IR free control circuitry to provide a structure-to-electrolyte "instant off" potential reading that is free of IR drop error.

Special precautions need to be observed when CP is applied to titanium-tubed condensers since titanium is susceptible to hydride embrittlement at higher more negative potentials. The general consensus appears to be that the protection potential in a titanium-tubed condenser should not be less positive than +0.40 Volts versus zinc, in order to guard against hydride embrittlement of the tubes. The control potential in an automatically controlled rectifier can be set to minimize the possibility of this occurrence.

In the past, the most commonly used reference electrode in surface condensers has been a piece of corroding pure zinc. Silver/silver chloride (Ag/AgCl) and copper/copper sulfate (Cu/CuSO4) are now being used more commonly. Individual anode leads are usually fed through a junction box that is provided with a current measuring shunt for each anode circuit. This allows the operator to determine if an anode is failing or has failed. Figure 2-6 provides a schematic of a typical impressed current design using an automatic potential controlled rectifier.

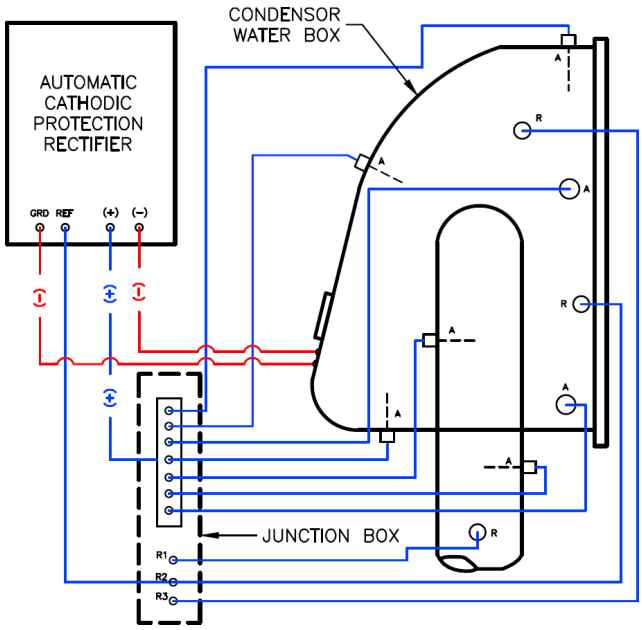


Figure 2-6
Schematic of a Waterbox Impressed Current CP System (A = Anode, and B = Reference Electrode)

2.3 Operation and Maintenance

Periodic surveillance of an impressed current cathodic protection system for a condenser or heat exchanger generally includes a check of the rectifier DC output every 2 months. More detailed inspections include measurement of the current to individual anodes and measurement of the structure-to-electrolyte potential. Galvanic systems generally do not have any monitoring equipment and anodes are typically replaced during outage of the equipment. For impressed current systems, the predominant method of determining whether protection has been achieved is the measurement of the structure-to-electrolyte potential using a permanently installed reference electrode. The protection potential that should be specified is a polarized “instant off” potential of +0.25 Volts vs. zinc, -0.75 Volts vs. Ag/AgCl and -0.85 Volts vs. a $Cu/CuSO_4$ reference electrode. An anode should be replaced during an outage when the individual anode currents, as measured through the shunts, are at zero, close to zero or have dropped substantially. This will require an inventory of the anode type and developing a work order for the task. In conjunction with the monitoring and maintenance program, plant electricians should be trained to provide the basic monitoring and testing services for the CP system. Training sessions should include corrosion and cathodic protection theory, record keeping, rectifier trouble shooting and procedures for measuring rectifier voltage, current and structure-to-electrolyte potential.

3
CP OF ATMOSPHERICALLY EXPOSED REINFORCED CONCRETE STRUCTURES

The evolution of cathodic protection technology for reinforced concrete structures has produced a variety of improvements and new developments in recent years. Some of these new developments include anode materials and configurations for impressed current systems, concrete specific reference electrodes, monitoring instrumentation, and galvanic systems using anodes embedded in conductive mortars and aluminum based thermal spray anodes. More recently, cathodic protection systems have been used in the preventative mode, where the system protects concrete structures that are not actively corroding, but are expected to do so in the future because of exposure. This section provides a review of the corrosion mechanism for steel-in-concrete and discusses the application of cathodic protection to atmospherically exposed reinforced concrete structures using galvanic and impressed current anode technology.

3.1 Corrosion Mechanism

Reinforcing steel in concrete normally does not corrode because of the formation of a passive oxide film on the surface of the steel due to the initial corrosion reaction. The process of hydration of cement in freshly placed concrete develops a high alkalinity, which in the presence of oxygen stabilizes the film on the surface of embedded steel, ensuring continued protection while the alkalinity is retained. Normally, concrete exhibits a pH above 12 because of the presence of calcium hydroxide, potassium hydroxide, and sodium hydroxide. Although the precise nature of this passive film is unknown, it isolates the steel from the environment and slows further corrosion as long as the film is intact. However, there are two major situations in which the passive film can be disrupted. These include:

- Chloride contamination, and
- Carbonation

Chlorides are the most common source of contamination that lead to corrosion of the reinforcing steel in concrete. Chloride ions can enter into the concrete from de-icing salts that are applied to the concrete surface or from saltwater in coastal environments. Other sources include admixtures (such as calcium chloride), contaminants, airborne salts and industrial brine. If chlorides are present in sufficient quantity, they disrupt the passive film and subject the reinforcing steel to corrosion. The levels of chloride required to initiate corrosion are extremely low. There have been many recommendations, both in the codes and in publications, for maximum chloride concentrations. However in the United States the acid soluble chloride threshold value typically used is 0.6 to 0.9 kg/m^3 (1.0 to 1.5 lb/yd^3) of concrete.[7]

[7] ACI 222R-01 (Reapproved 2010), "Protection of Metals in Concrete Against Corrosion", American Concrete Institute, Farmington Hills, MI.

Key Technical Point

Chlorides are the most common source of contamination that lead to corrosion of the reinforcing steel in concrete.

Chloride analysis is best performed under controlled conditions in a laboratory. Field testing kits are available to determine chloride content from powdered concrete samples using the titration method. Typically these kits are sufficiently accurate to provide a certain range which is useful for field applications. When obtaining concrete samples for chloride analysis, these should be obtained at the rebar depth. Also, chloride profiles vs. depth can be useful in calculating diffusion coefficients and estimating the time to reach chloride threshold values at rebar depth and therefore the initiation of corrosion.

Chlorides must be in soluble form, also referred to as "free" chlorides, to contribute to the corrosion reaction. Chemically bound chlorides in the concrete are not available to disrupt the protective film. When testing the content of chlorides in concrete it is important to note the difference between "acid-soluble" and "water-soluble" chlorides. Acid soluble chlorides include all chlorides both bound and free, whereas water soluble chlorides only include chlorides available to support corrosion. Over time, bound chlorides may be released and become available to contribute to the corrosion process.

Chloride ions within the concrete are usually not distributed uniformly and steel areas exposed to higher concentrations of chlorides will start to corrode first resulting in a breakdown of the oxide film. In other areas, the steel remains passive and no corrosion occurs. This uneven distribution may result in macro-cell corrosion. Figure 3-1 illustrates how a macro corrosion cell can develop from differences in chloride ion concentration.

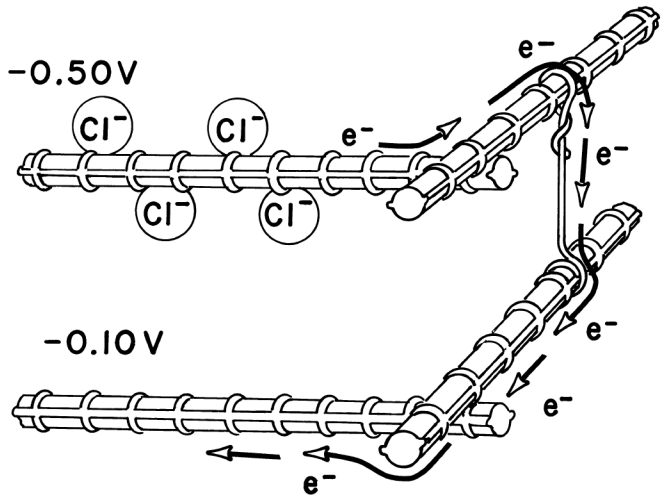


Figure 3-1
Differences in Chloride Ion Concentration Establish Differences in Electrochemical Potential

(Source: Corrpro Companies, Inc.)

Patching of delaminated and spalled concrete with conventional concrete is yet another example of the corrosion mechanism. Strong electrochemical macro-cells are established near the interface between the old chloride contaminated concrete and the new chloride-free concrete. The short distance between anode and cathode, together with the large difference in chloride concentration, result in strong potential gradients, which accelerate corrosion. Such a macro-cell is shown in Figure 3-2. In many cases, this kind of repair will require rehabilitation again in several years.

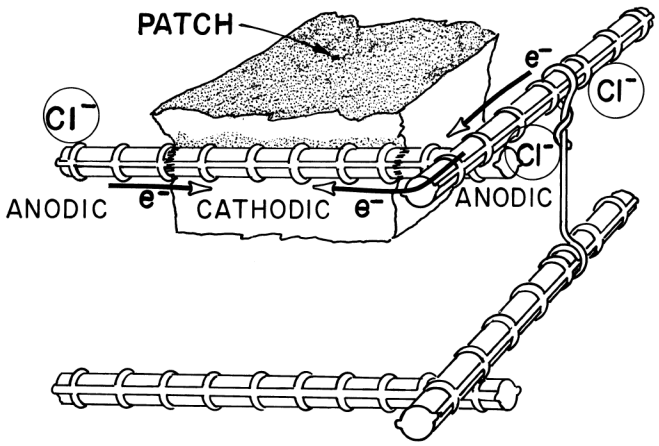


Figure 3-2
Macro-cell Corrosion though Concrete Patching

(Source: Corrpro Companies, Inc.)

Differences within the grain structure of the metal or different residual stress levels can also lead to corrosion. When chlorides are uniformly distributed around the steel, local action micro-cells form and dominate the corrosion process. Anodic and cathodic sites may be observed very close to each other on the same bar under such circumstances. This micro-cell effect generally leads to a type of localized corrosion known as pitting corrosion. In this case, metal loss from anodic sites creates a pit. As corrosion proceeds, the condition inside the pit becomes progressively more acidic and further loss occurs from the bottom of the pit rather from the sides. The cross-sectional area of the steel is progressively reduced to a point in which the steel can no longer carry the applied load.

Although not as common as chloride induced corrosion, another cause of corrosion of reinforcing steel in atmospherically exposed concrete, is carbonation. Carbonation is a process in which carbon dioxide from the atmosphere diffuses through the porous concrete and neutralizes the alkalinity of concrete. The carbonation process will reduce the pH to approximately 8 or 9 in which the oxide film is no longer stable. With adequate supply of oxygen and moisture, corrosion will start. The penetration of concrete structures by carbonation is a slow process, the rate of which is determined by the rate at which carbon dioxide can penetrate into the concrete. The rate of penetration primarily depends on the porosity and permeability of the concrete. It is rarely a problem on structures that are built with good quality concrete with adequate depth of cover over the reinforcing steel. The best way to check for carbonation is to retrieve a small core and treat it with phenolphthalein solution. This solution will change color (to purple) if the concrete pH is 10 or less. This change in color indicates the advancement of the carbonation front in the concrete.

All of the corrosion processes described above require oxygen. In the absence of oxygen, the corrosion rate is appreciably reduced even with chloride concentrations above the threshold level. However, keeping oxygen from reinforcing steel in the field is extremely difficult, if not impossible. When corrosion of reinforcing steel occurs, the corrosion products or rust can occupy several times the volume than the original steel, causing tensile forces to develop in the concrete. Since concrete is relatively weak in tension, cracks can develop as shown in Figure 3-3a, exposing the steel to even more chlorides, oxygen and moisture - and the corrosion process accelerates. As corrosion continues, delaminations (separations within the concrete and parallel to the concrete surface) occur (Figure 3-3b). Delaminations are usually located at, or near, the level of the reinforcing steel. Eventually pieces of concrete break away forming spalls in the concrete (Figure 3-3c), which require repair to maintain structural integrity.

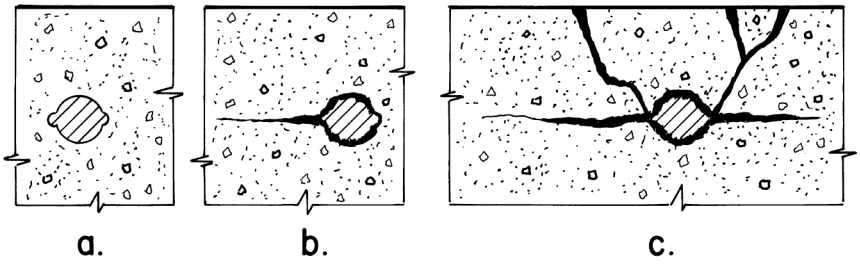


Figure 3-3
Corrosion Induced Cracking of Concrete

(Source: Corrpro Companies, Inc.)

3.2 Galvanic Anode Systems

A sacrificial or galvanic anode system for reinforced concrete uses a more reactive metal (anode) such as zinc or aluminum-zinc-indium (Al-Zn-In) to create a current flow. Galvanic anode systems are based on the principle of dissimilar metal corrosion and the relative position of different metals in the galvanic series. The direct current that is generated is a function of the potential difference between the anode and the reinforcing steel and the anode-to-electrolyte resistance. The galvanic anode will corrode during the process and is consumed. Current will flow from the anode, through the concrete, to the reinforcing steel surface. Galvanic anodes may be installed as cast anodes in soil or concrete, in contained forms that are attached to the concrete (such as pile jackets), or thermally sprayed onto the concrete surface to form a sacrificial coating.

Galvanic anode CP systems have the benefit of no auxiliary power supply and the advantage of being used on prestressed or post tensioned concrete without the risk of developing elevated potentials, which could lead to hydrogen embrittlement of the steel. The anode life is directly related to the mass of the anode material used and the current output. In some instances the life of a galvanic anode may be relatively short compared to an impressed current anode. Also, the current that is produced by the galvanic anode is a function of the environment (i.e., moisture and temperature conditions) and the output cannot be easily adjusted or controlled as with an impressed current CP system.

Key Technical Point

The current that is produced by the galvanic anode is a function of the environment (i.e., moisture and temperature conditions) and the output cannot be easily adjusted or controlled as with an impressed current CP system.

In a galvanic anode system, the anode is the most important component and there are a variety of materials and configurations available. NACE Publication 01105 provides a State-of-the-Art report for sacrificial cathodic protection of reinforced concrete elements.[8]

3.2.1 Discrete Galvanic Anodes

Discrete galvanic anodes are generally made of cast zinc that are installed in the concrete and connected directly to the reinforcing steel. Because of the high resistivity that is typical of concrete, discrete galvanic anodes that are directly embedded in concrete are typically not recommended for cathodic protection, as the high resistivity limits the current output and protection criteria for CP are difficult to achieve. To compensate for the reduced current, manufacturers offer zinc anodes encapsulated in a highly alkaline and conductive mortar that promotes the corrosion of the zinc and therefore increases current delivery. These discrete anodes are commonly referred to as "hockey pucks" and are best suited to reduce the ring or halo effect that is produced adjacent to newly repaired concrete areas (i.e., patch repair). Newer discrete galvanic anodes include zinc bars and mesh encapsulated in conductive mortar placed directly into excavated concrete.



Figure 3-4
Discrete Galvanic Anode Installation in Concrete Patch Repair

(Source: Vector Corrosion Technologies)

[8] NACE Publication 01105, "Sacrificial Cathodic Protection of Reinforced Concrete Elements – A State-of-the-Art Report", NACE International, Houston, TX.

3.2.2 Zinc Mesh Jacket Systems

Sacrificial cathodic protection jackets were initially developed to address corrosion of concrete piles in the tidal and splash zones. More recently this technology is being applied to columns, lintels, pedestals and other concrete structures that lend themselves to full encapsulation and where the concrete is sufficiently conductive to permit the operation of the jacket in the galvanic mode. CP jackets consist of a fiberglass form with an integral zinc mesh anode, connection hardware and cables (see Figure 3-5). The manufacturer supplies the jacket in two sections for ease of installation in the field. The jackets have pumping ports strategically placed so that the annular space between the concrete pile and jacket can be filled with concrete mortar. CP jackets for piles in seawater are sometimes supplemented with bulk zinc anodes below the water line. These jackets are most effective in the tidal zone up 10 to 15 feet above the mean sea level.



Figure 3-5
Zinc Mesh Pile Jacket System at the Base of a Cooling Tower

(Source: Structural Technologies)

3.2.3 Metalized Anodes

Metalizing technology consists of melting a metal, atomizing the molten particles and propelling them on to a prepared substrate. The technology is commonly used for corrosion protection of metals, abrasion resistance, rebuilding and construction of parts and components. Most applications in the field use wire-arc or combustion guns (flame spray). The development of these techniques has improved application of thermally sprayed anodes for cathodic protection of reinforced and prestressed concrete structures.

Thermal spray technology has been successfully used to protect structures of various types and configurations including bridge components, intake structures, dock facilities, balconies and parking garages. The concrete surface is prepared by light abrasive blasting and the anode material is sprayed on the concrete surface to form a coating. Although pure zinc wire has been commonly used for this application, more recent developments include a proprietary Aluminum-Zinc-Indium (Al-20Zn-0.2In) wire alloy with higher open circuit potential and higher current

delivery than pure zinc. Figure 3-6 shows the arc spray application of pure zinc to an intake structure concrete wall.



Figure 3-6
Arc Spray Application of Sacrificial Zinc Anode to an Intake Structure Concrete Wall

(Source: Structural Technologies)

The current that is produced by the metallized anode is a function voltage difference between the anode and reinforcing steel and the environmental conditions, which affect the anode-to-electrolyte resistance. Zinc anodes must be high purity with a maximum iron content of 14 ppm. This ensures the anode material is optimized for cathodic protection. Chemical treatment of zinc anodes with humectants has been performed on some applications. This technology helps reduce the contact resistance at the anode-concrete interface and can result in a net increase in current output from the zinc anode.

Metallized anodes are generally installed at a thickness of 15-20 mils. Perforated zinc plates are used to connect the coating to the rebar. Protective coatings may be applied over the zinc to prevent undue corrosion and premature consumption of the anode, particularly in aggressive environments. Also, coatings can be applied over the anode for aesthetic purposes. Any coating that is used should be compatible with the anode and allow vapor and moisture transmission. This will prevent the build-up of oxides at the anode interface and prevent disbonding of the coating.

3.3 Impressed Current CP Systems

Impressed current systems for atmospherically exposed reinforced concrete structures require the following basic components:

- Rectifier
- Inert anode material, such as catalyzed titanium anode mesh
- Wiring and conduit
- Instrumentation, such as embedded silver-silver chloride (Ag-AgCl) reference electrodes

Rectifiers for concrete applications are typically designed to provide constant current control at relatively low current outputs. Current densities for cathodic protection of existing reinforced

concrete may range between 0.1 and 1.0 mA/ft^2 (1.0 and 10 mA/m^2) depending on the environment and amount of rebar corrosion. Lower current densities may be used for cathodic protection of new reinforced concrete structures where the chloride ions have not yet penetrated to the rebar surface. The concrete structure may be divided into isolated anode zones based on the steel density and environmental conditions. Therefore rectifiers for concrete applications may have multiple circuits to control the current delivery to each anode zone. The concrete structure is typically instrumented with embedded silver-silver chloride (Ag-AgCl) reference electrodes that are used to test and monitor the structure potential. A minimum 100 mV of polarization decay or development is typically used as the criteria for cathodic protection of reinforcing steel in concrete. Guidelines regarding CP criteria, design, installation practices, energizing, system adjustment, operation and maintenance of impressed current cathodic protection systems for atmospherically exposed reinforced concrete structures are given in NACE Standard Practice SP0290.[9]



Key Technical Point

Current densities for cathodic protection of existing reinforced concrete may range between 0.1 and 1.0 mA/ft2 (1.0 and 10 mA/m2) depending on the environment and amount of rebar corrosion.

3.3.1 Titanium Mesh Anodes

Titanium mesh anodes are available in a variety of forms including expanded titanium anode mesh, ribbon mesh and discrete anodes. Titanium anode mesh anodes are typically encapsulated in a concrete overlay or shotcrete material, although ribbon mesh may be installed in slots with a cementitious grout or used in new construction with plastic rebar clips to prevent the anode from contacting (shorting to) the rebar. The anodes are composed of a precious metal oxide catalyst that is sintered to an expanded titanium mesh substrate. By using inert anode materials, such as catalyzed titanium, anode consumption is minimized. One of the main benefits of catalyzed titanium is that its life expectancy can be determined through accelerated life testing. Design current density ratings are typically kept to a maximum value of 10 mA/ft^2 (110 mA/m^2) of anode surface, which is the Federal Highway Administration (FHWA) limit. NACE Standard TM0294-2007 gives procedures for accelerated life testing of these anodes.[10] Based on test results using this method, it has been found that the life expectancy of catalyzed titanium anodes can exceed 40 years. A schematic of an impressed current CP system using catalyzed titanium anode mesh is shown in Figure 3-7.

[9] NACE SP0290-2007, "Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures", NACE International, Houston, TX.

[10] NACE Standard Test Method TM0294-2007, "Testing of Embeddable Anodes for Cathodic Protection of Atmospherically Exposed Steel Reinforced Concrete" NACE International, Houston, TX.

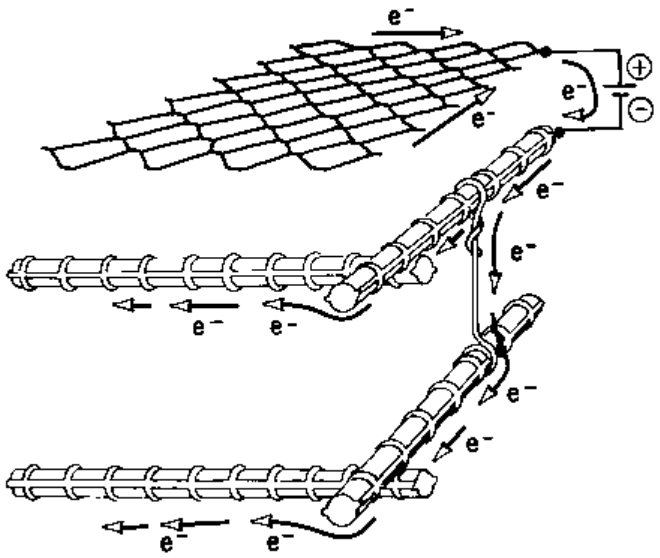


Figure 3-7
Schematic of a Catalyzed Titanium Anode Mesh Impressed Current CP System

(Source: Corrpro Companies, Inc.)

3.3.2 Conductive Coatings

Conductive coatings can be solvent based or water based materials that are loaded with carbon filler to make them electrically conductive and black in color. With these systems platinized niobium wire is typically used as the primary anode that delivers current to the conductive coating, which in turn discharges current into the concrete. The conductive coating system may be over-coated with a variety of top coats (paints), primarily for aesthetic purposes. These systems have been used on a variety of structures with mixed results. Conductive coating anodes are not recommended for wet concrete environments, such as splash zones or areas where ponding and water leakage is expected. Blistering and disbonding of the anode material has been experienced in these environments. Caution should be exercised when placing the anode material on concrete surfaces to avoid shorting to steel wire ties, chairs and directly to exposed rebar.

3.3.3 Metalized Zinc Anode

The application of metalized zinc anodes as a sacrificial anode using thermal spray technology has been discussed in a previous section. Metalized zinc anodes are also used in the impressed current mode by connecting the anode to a power source such as a rectifier. As with other impressed current anodes, caution should be exercised during installation to avoid shorting the anode to the reinforcing steel. This precaution is not necessary when using the anode in the galvanic mode. When used in the impressed current mode, metalized anodes provide low resistance to the passage of current because they are metallic and the large contact surface area is inversely proportional to the anode-concrete resistance. By controlling the current output from the anode via the rectifier, current densities can be optimized. This may result in longer life expectancies for the zinc anode as compared to its use in the galvanic mode. Similar to galvanic anode systems, the zinc anode can be top coated for protection from the environment as well as for aesthetic purposes. The zinc can also be chemically treated to minimize contact resistance if desired.

3.3.4 Discrete Anodes

Discrete anodes can provide localized impressed current cathodic protection to the reinforcing steel. These anodes are available in a variety of configurations and include ceramic based tubular anodes and titanium mesh anodes that are installed in pre-drilled holes in the concrete structure. After the anodes are installed the holes are filled with a cementitious grout. One advantage of these anodes is that they can be placed deeper in the concrete, promoting delivery of CP current to the steel rebars that are farther away from the surface.

3.4 Operation and Maintenance

All cathodic protection systems should be inspected as part of a preventive maintenance program to minimize in-service failure. Inspection of impressed current systems should include a check for electrical shorts of the anode system to rebar, ground connections, rectifier meter accuracy, rectifier efficiency, and circuit resistance. Annual surveys should be conducted to verify that the CP system is meeting criteria for protection and typically a minimum of 100 mV of polarization should be achieved at the most anodic sites in accordance with NACE SP0290. The accuracy of permanently embedded reference electrodes should be evaluated during these surveys. Rectifiers should be checked at two (2) month intervals, or at such intervals as necessary to ensure effective operation of the system. Evidence of proper operation can be normal current and voltage output, a signal indicating normal operation, or a satisfactory polarized potential of the reinforcing steel. Remedial measures should be taken when annual surveys and inspections indicate that protection levels have been compromised.

The output of a galvanic or sacrificial anode system is reduced to some extent in very low humidity environments because the passage of current through the concrete substrate is dependent on the resistivity of the concrete. Current delivery is self-regulating and polarization levels may vary based on the environmental conditions. The current is usually monitored at specific test sites that allow measurement of the current through a wire connection in a junction box. Half-cell potential measurements are often taken using a standard reference electrode, and the potential shift usually gives an indication of the area of influence. Testing of the galvanic anode performance is usually conducted on an annual basis in conjunction with the corrosion survey.

4
CP OF INTAKE STRUCTURES

Power generating facilities require large quantities of cooling water as part of the electrical generating process for cooling of the condensers. The water sources most frequently used include rivers, lakes, reservoirs, brackish water and seawater. Even at plants with closed cooling systems, makeup water from other sources is required. The water must be screened and the debris removed in the intake structure before use, to allow proper operation of the circulating and service water pumps and to prevent clogging of the tubes and openings in the condensers and heat exchangers.

4.1 Corrosion Mechanism

Power generating facility intake structures consist of a variety of materials and components which are installed at the cooling water source. The intake structure, or circulating water pump house as it is sometimes referred to, usually consists of stop gates, trash racks, flow through traveling screens, circulating water pumps and spray wash pumps. The trash rack and traveling screen are intended to prevent the flow of debris, marine life, and other physical pollutants from entering into the cooling water system. The trash rack, usually installed at the mouth of the intake structure, prevents large material from entering into the intake bays. The traveling screens consist of frames, rollers, and baskets, and are periodically rotated to collect debris which is then washed from the screen by water which is circulated from the screen wash pump. Circulating water pumps collect the water which flows into the intake bay. The water is then distributed throughout the cooling system for the power generating facility. Figure 4-1 provides a view of a typical intake structure with flow-through traveling screens.

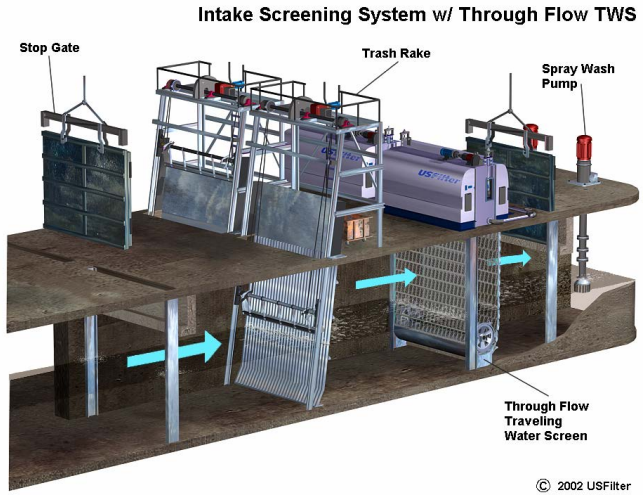


Figure 4-1
Typical Screening System for Intake Structure

(Source: US Filter)

A typical intake structure for a 1,000 megawatt generating facility may consist of as many as 8-12 intake bays which are typically 10-14 ft (3-4 m) in width and can be as deep as 60-80 ft (18-24 m). The intake bays are generally constructed of reinforced concrete. The water which flows into the intake bay can flow at a rate in excess of 2-ft per second (0.6 m per second). The corrosion problems encountered for the intake structure materials are primarily associated with the coupling of dissimilar metals exposed to a corrosive environment.



Key Technical Point

The corrosion problems encountered for the materials which comprise an intake structure are primarily associated with the coupling of dissimilar metals exposed to a corrosive environment.

Traveling screens typically consist of mild steel frames with stainless steel or copper baskets. In addition, various appurtenances for the traveling screens, such as rollers and support frames can be made from different materials. Often, the intake structure appurtenances are directly coupled to the reinforcing steel within the intake bay through a common grounding system. This condition also serves to accelerate the potential for corrosion of the traveling screens, trash racks, and circulating water pumps. EPRI Report 1009672 provides guidelines regarding the maintenance of circulating and service water intake screens and debris removal equipment.[11]

Corrosion control considerations for intake structures are usually limited to the application of cathodic protection and the selection of non-corrosive materials, such as stainless steel. Protective coating systems for corrosion control may have limited use because of the abrasion that results from the physical movement of the equipment. The flow of aggressive water against the surfaces of the trash racks, traveling screens, and circulating water pumps will have a detrimental effect on the adhesion of the coating and can result in rapid deterioration of any protective coating system. As such, the application of an effective cathodic protection system is considered one of the most effective methods to mitigate corrosion of the intake structure components.

4.2 Cathodic Protection

The cathodic protection design philosophy for intake structures is similar to that of condenser waterboxes. It includes use of historical data, calculations and if possible on-site testing of existing structures. As in the case of condenser water boxes, the impressed current cathodic protection system is usually the preferred approach for corrosion control of traveling screens and trash racks. Galvanic anode systems often require a large volume of anode material to provide a sufficient amount of current to achieve protection and provide a reasonable cathodic protection system life. Long slender sacrificial anodes (either zinc or magnesium) can be affixed to the baskets of traveling screens and heavier anodes can be attached to the pumps, sluice gates and piling in front of the intake structure.

[11] EPRI Report 1009672, "Circulating and Service Water Intake Screens and Debris Removal Equipment Maintenance Guide", December 2004, Electric Power Research Institute, Palo Alto, CA.

Key Technical Point

As in the case of condenser water boxes, the impressed current cathodic protection system is usually the preferred approach for effective corrosion control of traveling screens and trash racks. Galvanic anode systems often require a large volume of anode material to provide a sufficient amount of current to achieve protection and maintain a reasonable cathodic protection system life.

Impressed current systems can be designed with anodes mounted on non-metallic standoffs to the intake structure wall (Figure 4-2). The dielectric anode shield extends beyond the frame to provide improved current distribution to the structure and limits the pick-up of current on the reinforcing steel inside the intake structure floor and walls. Anode assemblies may be provided with MMO coated titanium or platinum current emitting surfaces.

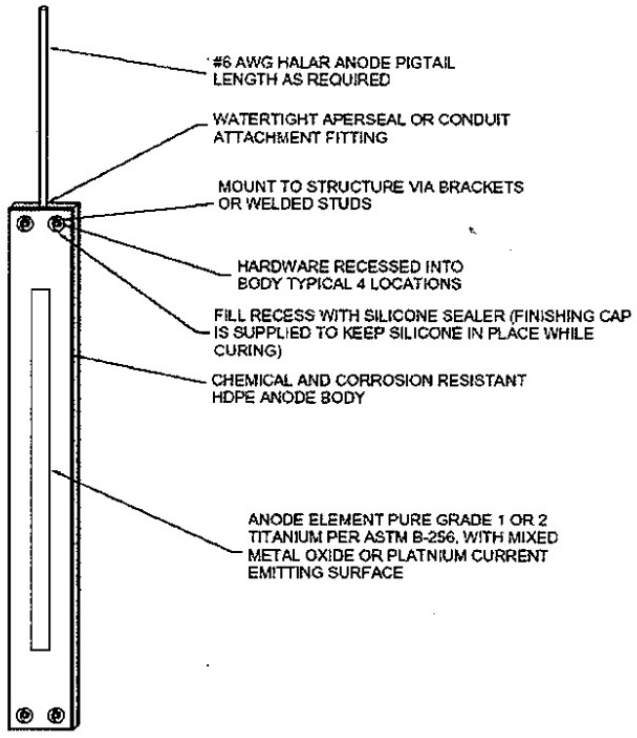


Figure 4-2
Impressed Current Anode Mounted on Non-Metallic Standoff

(Source: Norton Corrosion Limited)

Impressed current anodes can also be installed inside of perforated nonmetallic pipe (Figure 4-3). This design allows easy replacement of the anode without the use of divers. The anode tube assembly can also be designed with perforations on one side (180º). The non-perforated side is installed facing the concrete wall. This forces direct current to flow outwards to the structure and

reduces pick-up on the rebar surface. The anode tube design also provides mechanical protection to the anode from debris in the water.

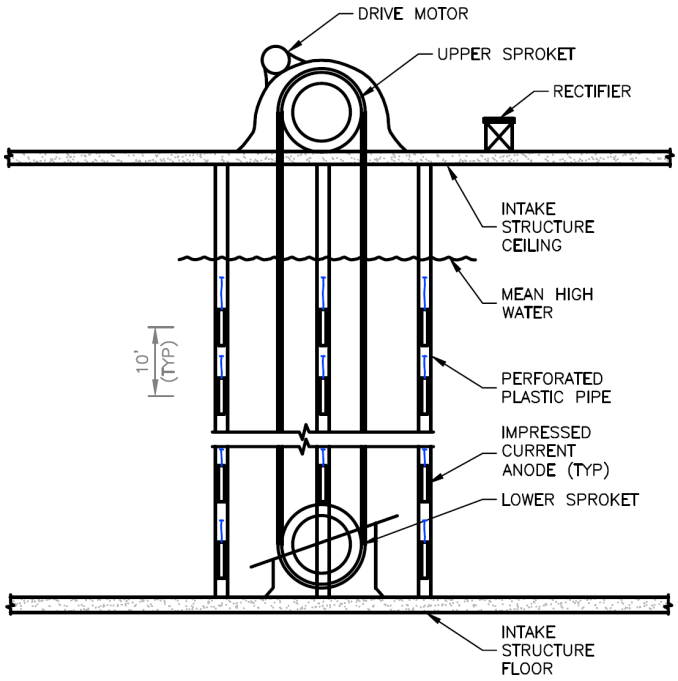


Figure 4-3
Impressed Current Protection of Traveling Screens using Perforated Anode Tubes

4.3 Operation and Maintenance

As with other impressed current cathodic protection systems, periodic surveillance of an intake structure system generally includes a check of the rectifier DC output every 2 months. More detailed inspections include measurement of the current to individual anodes and measurement of the structure-to-electrolyte potential. Galvanic systems generally do not have any monitoring equipment and anodes are typically replaced during outage of the equipment. For impressed current systems, the predominant method of determining whether protection has been achieved is the measurement of the structure-to-electrolyte potential using a permanently installed reference electrode. The protection potential that should be specified is a polarized "instant off" potential of +0.25 Volts vs. zinc, -0.75 Volts vs. Ag/AgCl and -0.85 Volts vs. a $Cu/CuSO_4$ reference electrode. An anode should be replaced during an outage when the individual anode currents as measured through the shunts are at zero, close to zero or have dropped substantially. This will require an inventory of the anode type and developing a work order for the task. In conjunction with the monitoring and maintenance program, plant electricians should be trained to provide the basic monitoring and testing services for the CP system. Training sessions should include corrosion and cathodic protection theory, record keeping, rectifier trouble shooting and procedures for measuring rectifier voltage, current and structure-to-electrolyte potential.

5
CP OF STEEL PILING IN SOIL

Steel piles have been used in underground applications for many years to transmit loads to lower levels or to resist lateral pressures due to earth and water. Pipe and H-piles are used as load-bearing foundations for structures and sheet piles have been used as structural members for dams, floodwalls and bulkheads, and for cofferdams used during construction. Caissons may be constructed with external casings consisting of pipe piles. The casings may serve as a form for the placement of liquid concrete inside the caisson and around the reinforcement. While no structural failures have been attributed to corrosion of underground piles at power plants, there is concern that loss of section due to corrosion might occur on steel piles, which could compromise the structural integrity of the various structures. This concern is enhanced by corrosion of steel piles that are driven into different soil environments and the results of corrosion investigations and research conducted by the National Bureau of Standards (NBS)[12] and the National Cooperative Highway Research Council (NCHRP)[13].

5.1 Corrosion Mechanism

The corrosion rate of steel piles in soil is influenced by a number of corrosion related parameters. These include soil resistivity, pH, chloride content, sulfate content, sulfide ion content, soil moisture, and oxygen content within the soil. Measurement of these parameters will give a general indication of the corrosivity of a soil. NACE International Publication 05101 provides a state-of-the-art report on corrosion of steel pilings in soil.[14]

The effect that differential aeration corrosion has on buried piling is given in Figure 5-1. Factors which affect the rate of corrosion include the relative area ratio of the anode and cathode, soil corrosivity and stratification of the soil. When the cathode is large and the anode is small, a large current is supported by the cathode and that current is concentrated at the anode, leading to high rates of attack at the anode. Stratification of the soil creates ideal conditions for differential aeration cells, such as where wet clays or regions below the water table that are deficient in oxygen become the anodes, while oxygen rich soils, such as porous sands, become the cathodes.

[12] NBS Monograph 58, "Corrosion of Steel Pilings in Soils", Reprinted October 1962, National Bureau of Standards (now National Institute of Standards and Technology), Gaithersburg, Md.

[13] NCHRP Report 408, "Corrosion of Steel Piling in Nonmarine Applications", 1998, National Cooperative Highway Research Program, administered by the Transportation Research Board (TRB), Washington, DC.

[14] NACE International Publication 05101, "State-of-the-Art Survey on Corrosion of Steel Piling in Soils", NACE International, Houston, TX.

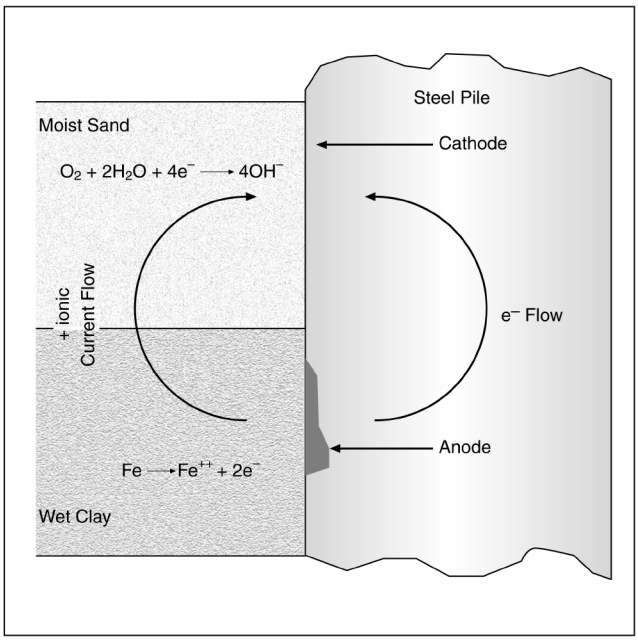


Figure 5-1
Schematic showing the Differential Aeration Corrosion Cell on a Buried Steel Pile

(Source: NACE International Publication 05101)

The position of the water table with respect to the steel pile is probably the most important factor affecting the corrosion of steel piling in soil, as little corrosion has been found on piling below the water table. As indicated above, most instances of severe underground corrosion are a result of differential aeration. When the entire structure is below the water table, oxygen concentrations near the piling are uniformly low and differential aeration cells do not develop.

Key Technical Point

The position of the water table with respect to the steel pile is probably the most important factor affecting corrosion of steel piling in soil, as little corrosion has been found on piling below the water table.

In general, the corrosion behavior of steel piling in soil can be divided into two categories, corrosion in disturbed soil and corrosion in undisturbed soil. A disturbed soil is a soil in which digging, backfilling or other soil upheaval has taken place. Driven steel piles generally have the majority of their length in undisturbed soil. However, excavation and backfilling for footings and pile caps create a region of disturbed soil near the top of the piles, increasing the availability of oxygen and the probability of corrosion.

A major contributor to increased corrosion rates of driven steel piles in soil is the availability of oxygen. In general, oxygen content is greater near the upper portion of the pile, greater in disturbed soils, and greater in soil near ground water. Soil disturbance in the upper region of the pile may create areas of differential aeration within and just below the disturbed soil zone. This may lead to increased pitting corrosion of the steel piles within or near the disturbed zone.

Localized corrosion cells may exist in some miscellaneous fills that can lead to increased corrosion rates of driven steel piles. These miscellaneous fills may include combinations of natural soils (clays and sands), construction debris, as well as waste inorganic materials. Increased corrosion rates have been documented in soils where the pH was 5.5 or less and the soil resistivity was below 1,000 ohm-cm.

When steel piles are used in corrosive soil or corrosive water, special corrosion protection considerations for the steel piling are needed. The extent of corrosion protection for steel piles will depend on the subsurface geology, the location of the groundwater table and the depth to which the soil has been disturbed. Corrosion mitigation strategies may include the need for additional corrosion allowance in the thickness of the metal to compensate for loss of section that may occur from corrosion, the use of protective coatings, and/or the application of cathodic protection.

5.2 Cathodic Protection

Cathodic protection of steel piling in soil is almost always accomplished using the impressed current method. This is because of the significant current that is required to protect the extensive area of bare metal surface. Sacrificial anodes that are installed in the soil will provide limited protection to the piling and will consume rapidly. Furthermore, as with other structures at nuclear power plants, the piling is connected to the copper grounding grid (station ground). This not only increases the corrosion rate of the steel piling due to the dissimilar metal coupling effect, but also increases the current demand for CP of the piling, as much of the current will be received on the copper grounding.



Key Technical Point

Cathodic protection of steel piling in soil is almost always accomplished using the impressed current method. This is because of the significant current that is required to protect the extensive area of bare metal surface.

A distributed anode system will provide more uniform current distribution to the piles compared to shallow or deep anode remote beds, and is the preferred method for cathodic protection of these structures. For new piling, cathodic protection may be applied using distributed anodes that are installed at the same time as the piling (Figure 5-2). The design should include bonding to provide electrical continuity of the piles. The primary option available to mitigate corrosion of existing piling in soils is the application of cathodic protection using the impressed current method. The distributed method of protection for buried piling is similar to the methods used for cathodic protection of buried piping. Each system requires a rectifier, impressed current anodes, buried cabling, anode lead junction boxes, system ground connection and test stations with permanently installed reference electrodes.

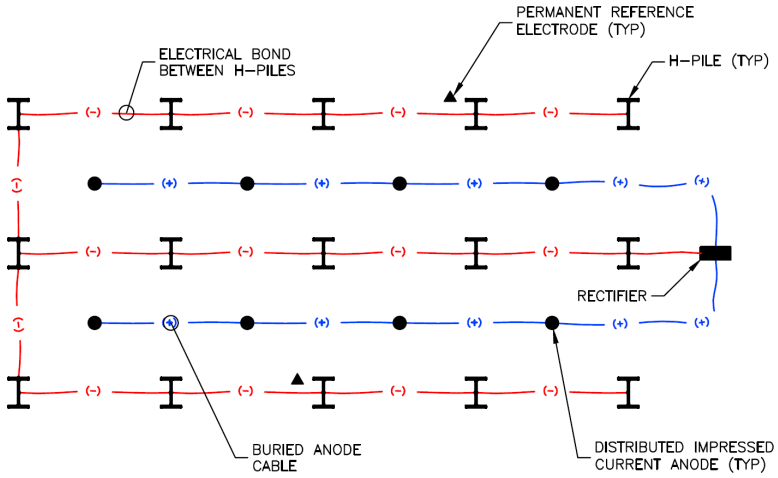


Figure 5-2
Schematic of a Distributed Anode Impressed Current System for Buried H-piles

Abrasion-resistant coatings can be applied to new steel piling to reduce the total current demand. If this alternative is selected, protection of the coating from damage during the driving operation, coating repair strategies, and the method of field coating pile splice sections should be developed. As with cathodic protection for buried pipelines that are coated, the CP system for buried piling is used to protect the voids or holidays in the coating.

5.3 Operation and Maintenance

The polarized -850 mV (CSE) criterion is the most commonly used criteria for cathodic protection of buried and submerged metallic structures and is one of three identified for steel and cast iron piping referenced in NACE SP0169. This criterion states that adequate protection is achieved when a negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode is achieved. The polarized potential can be defined as the potential across the structure/electrolyte interface that is the sum of the corrosion potential (E_{corr}) and the cathodic polarization. The polarized potential is measured directly after interruption of all current sources and is often referred to as the "Off" or "Instant-Off" potential.

Guidelines regarding monitoring and maintenance of CP systems can be found in NACE SP0169. As a minimum, the DC output of the cathodic protection rectifiers should be checked every 2 months and any deficiencies to the CP systems should be corrected in a timely manner. The effectiveness of the CP systems should be evaluated annually. Annual surveys may consist of anode junction box current readings and the measurement of polarized instant-off structure-to-soil potential at the test stations. In conjunction with the monitoring and maintenance program, plant electricians should be trained to provide the basic monitoring and testing services for the CP system. Training sessions should include corrosion and cathodic protection theory, record keeping, rectifier trouble shooting and procedures for measuring rectifier voltage, current and structure-to-electrolyte potential.

6
CP OF UNDERGROUND STORAGE TANKS

At nuclear power plants, underground storage tank (UST) systems are typically used for the storage of diesel fuel oil (DFO) and lube oil. In particular, the DFO tanks are used to provide fuel oil for the standby diesel generators. The UST systems include the underground tanks and their associated piping (i.e., fill pipe, vent pipe, overflow, recirculating inlet and outlet lines, etc.). DFO tanks are typically large diameter underground storage tanks with 20,000 to 60,000 gallon capacities, whereas the lube oil tanks are smaller in capacity. Tanks may be single-wall or double-wall construction and are typically constructed of welded carbon steel plate. The metallic piping systems may be carbon steel and/or stainless steel.

Unprotected underground metallic components of the UST system can corrode and release product through perforations in the tank walls and piping. All metal components of the UST system that are in contact with the ground and routinely contain product must be protected from corrosion. The two common methods for protecting metal UST components from corrosion are cathodic protection and isolating the metal component from the corrosive environment, such as installing the tanks and piping in vaults. Tanks and piping may also be constructed of non-corrodible materials, such as fiberglass-reinforced plastic (FRP). If FRP is used then cathodic protection is not required.

6.1 Corrosion Mechanism

USTs and their associated steel piping systems are typically coated with polyurethanes, epoxies or reinforced plastic compounds. The tanks and associated piping systems are typically grounded to reduce the effects of hazardous voltages associated with lightning and fault currents in the earth. Insulating devices that are designed to provide electrical isolation for cathodic protection are typically not installed in UST systems at nuclear power plants. Because of the dissimilar metal couplings that exist through the copper grounding, corrosion rates can significantly increase on the steel tanks and piping as a result galvanic corrosion activity. Corrosion can begin as pitting on the metal surface in areas where the coating is damaged. As the pits become deeper, holes in the tank wall may develop and even a small corrosion hole can result in a significant release over time.

Underground storage tanks are almost always subject to differential oxygen concentration cells, especially when placed under pavement (Figure 6-1). Areas with lower oxygen concentration become anodic and corrode with respect to areas of higher oxygen concentration (cathode). This may result in more severe corrosion attack at the bottom of the tank, since oxygen concentration is primary dependent on diffusion from the soil surface.

Key Technical Point

Underground storage tanks are almost always subject to oxygen cell attack, especially when placed under pavement. Areas with lower oxygen concentration become anodic and corrode with respect to areas of higher oxygen concentration (cathode).

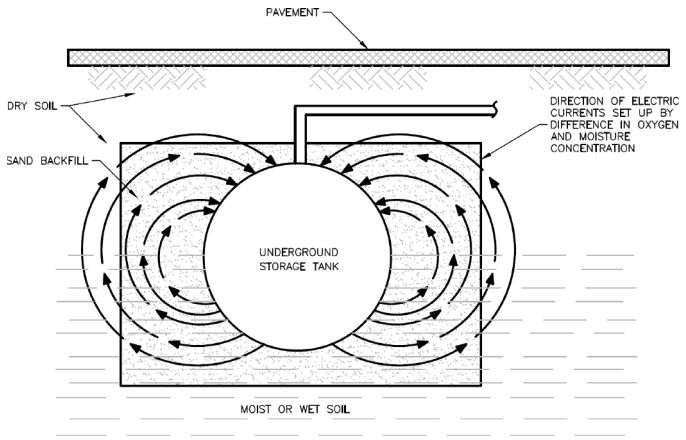


Figure 6-1
Underground Storage Tank Oxygen Concentration Corrosion Cell

If native soils were used as a backfill during installation of the UST, then the exterior tank walls may contact more than one stratum of soil and subject the steel surface to differential soil concentration cells. Soil characteristics also substantially affect the type and rate of corrosion occurring on the UST system. For instance dissolved salts increase the conductivity of the soil (electrolyte) and help determine reaction rates at the anodic and cathodic sites. Soil moisture, pH (a measure of acidity), and the presence of sulfides also influence corrosion. These factors, and perhaps others, interact in a complex fashion to influence corrosion of a UST system.

6.2 Cathodic Protection

6.2.1 Introduction

Corrosion of UST systems may be minimized by proper application of cathodic protection. CP may be applied using the sacrificial (galvanic) anode method or by using a distributed anode impressed current system. Guidelines regarding the design, installation and testing of cathodic protection systems for underground storage tanks and piping can be found in API Recommended Practice 162[15], NACE SP0169, NACE RP0285[16], STI R892[17] and NACE Publication 38477[18]. If

[15] API Recommended Practice 1632, "Cathodic Protection of Underground Petroleum Storage Tanks and Piping Systems", Third Edition, May 1996 (Reaffirmed, June 2002), American Petroleum Institute, Washington, DC.

[16] NACE RP0285-2002, "Corrosion Control of Underground Storage Tank Systems by Cathodic Protection", NACE International, Houston, TX.

the galvanic anode method is used, the tank and piping systems should be electrically isolated from station ground and all other structures (product and vent piping, hold-down straps, liquid-level monitoring systems, interstitial space monitors, conduit lines, etc.) for the CP system to perform as designed. This will require isolation of components and installation of dielectric fittings in the piping system to contain the CP current. If dielectric fittings are installed, then consideration should be given to using solid state DC decoupling devices across the insulating joints. The DC de-coupler will act as an open circuit for DC and as a short circuit for AC and lightning surges; thereby maintaining effective grounding while ensuring that the CP current is delivered to the tank and associated piping.

US NRC Regulatory Guide 1.137 provides regulatory guidelines regarding corrosion protection for standby diesel generator fuel-oil systems.[19] This regulation requires that a protective coating and an impressed current system be provided for buried supply tanks not located within a vault and other buried portions of the system in accordance with NACE Standard RP-01-69 (now SP016). In addition, the impressed current system should be designed to prevent ignition of combustible vapors or fuel oil present in the fuel oil system for standby diesel generators. Additional requirements pertaining to the corrosion protection of UST systems may also be found under local State and Federal EPA regulations.

6.2.2 CP of New UST Systems

Cathodic protection systems for new UST Systems and their associated piping may consist of:

- Factory-fabricated galvanic anode systems,
- Field-installed galvanic anode systems, or
- Field-installed impressed current anode systems.

Factory-fabricated system galvanic anode systems are available for new USTs. The protection system consists of three basic parts: a) a coating with high di-electrical qualities, b) electrically isolated fittings, and c) sacrificial anodes. The Steel Tank Institute provides a pre-engineered STI-P3® tank that is available in single-wall or double-wall construction with cathodic protection (Figure 6-2). The size and number of anodes to protect the tank from corrosion is pre-determined by calculations based on the desired life, tank surface area, the quality of the coating, anode type, anode size and range of soil resistivity that is anticipated at the site where the tank(s) will be installed. Zinc is the most commonly used anode for factory-prefabricated systems, although magnesium anodes are more effective in higher soil resistivities or on tanks where temperatures are expected to exceed 49ºC (120ºF). Anodes can be attached directly to the tank or wired through a test station to the tank. CP monitoring is provided using a buried copper-copper sulfate reference electrode. If electrical isolation is not provided or the dielectric fittings are shorted

[17] STI R892, "Recommended Practice for Corrosion Protection of Underground Piping Networks Associated with Liquid Storage and Dispensing Systems", Steel Tank Institute / Steel Plate Fabricators Association, Lake Zurich, Illinois.

[18] NACE Publication No. 38477, "How to Test Cathodic Protection on Underground Storage Tanks", NACE International, Houston, TX.

[19] U.S. NRC Regulatory Guide 1.137 "Fuel-Oil Systems for Standby Diesel Generators", October 1979, Rev. 1, Nuclear Regulatory Commission, Rockville, MD.

externally, then the system will not function as designed. Impressed current systems with distributed anodes may be used for new UST systems with or without electrical isolation.

Key Technical Point

Factory-fabricated system galvanic anode systems are available for new USTs. The protection system consists of three basic parts: a) a coating with high di-electrical qualities, b) electrically isolated fittings, and c) sacrificial anodes.

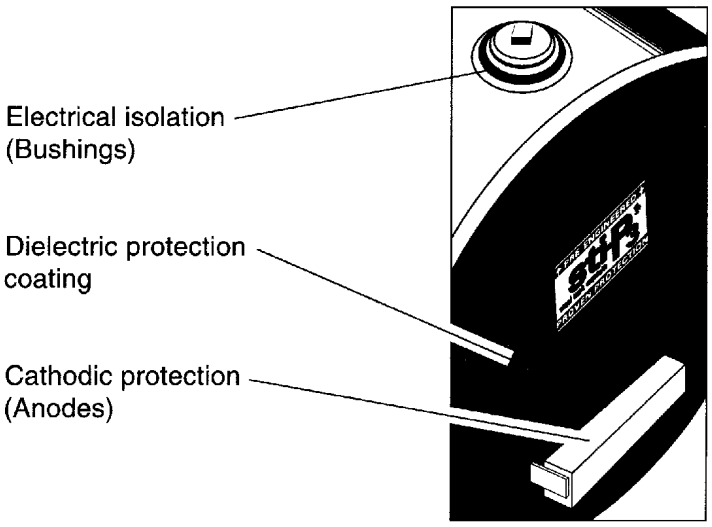


Figure 6-2
STI-P3® Underground Storage Tank with Pre-Engineered Galvanic Anode CP System

(Source: Steel Tank Institute)

6.2.3 CP of Existing UST Systems

Prior to designing a CP system for an existing UST system it is necessary to gather as-built construction information showing the size, configuration and condition of the tank(s) and other associated piping or equipment. Knowledge of the materials of construction for the tanks and piping is necessary, as is the location of other underground structures and piping in the vicinity of the proposed system. The operating history, leak history (if any), repairs, replacement of system components, and operating data of any previous CP systems including the type of system, placement of anodes, placement of permanently installed reference electrodes and level of protection should be evaluated prior to designing a CP system for an existing UST.

On site testing may include gathering soil chemistry data from near-by soil borings. When available, soil samples should be placed in sealed containers and analyzed for resistivity, pH, sulfide ion concentration, chloride ion concentration, and moisture content. Tests should be conducted to evaluate the native (as-found) structure-to-soil potential of the UST system and its associated piping. This will require use of a portable copper-copper sulfate reference electrode

(CSE), test leads and a high impedance voltmeter. Electrode placement is important when collecting the structure-to-soil potential data and proper notation of each electrode reading is required. Potentials should be collected over the centerline of the tank, at the tank extremities and over the associated piping systems. If asphalt or concrete pavement is present over the tank(s), this may require drilling small ½" diameter holes through the asphalt and/or concrete for reference electrode placement. Alternatively, soil access points may be installed over the tank to allow placement of a portable reference electrode.

Test wells (small diameter perforated PVC pipes) may also be installed next to the tank. The test wells allow measurement of the tank-to-soil potential using a portable reference electrode with a submersible adapter. If permanent reference electrodes are installed beneath the tank(s) or next to the tank(s), their accuracy and stability should be determined prior to use. The native structure-to-soil potential measurements may be used for determining the presence of any stray current interference, such as stray currents from DC welding equipment and DC powered motors. The native structure-to-soil potentials are also used as a basis for determining polarization development during current requirement testing and for assessing cathodic protection criteria.

Current requirement testing simulating the effects of a permanently installed CP system, provide an estimation of the total current demand for cathodic protection of the UST system. During a current requirement test, direct current is forced to flow from a temporary anode groundbed to the tank(s) being studied using a portable test rectifier or other DC power supply. Temporary anodes for current requirement tests may consist of isolated buried metallic structures or metal rods that are driven into the soil. Prior to the current requirement testing native (as-found) structure-to-soil potentials are measured over the structure. The rectifier is then energized and structure is allowed to polarize. The output of the test rectifier is adjusted and potential measurements are obtained. The level of polarization as a function of applied current is determined and extrapolations are made regarding current distribution and the amount of cathodic protection needed. Because of the common grounding effect, the current required to cathodically protect the UST system is significantly greater than that required to protect an isolated system. Buried foundations, tie-downs and reinforcing ribs that are electrically continuous with the tank will increase the current demand for cathodic protection. As such, impressed current systems are typically required for CP of existing UST systems (Figure 6-3).



Key Technical Point

Because of the common grounding effect, the current required to cathodically protect the UST system is significantly greater than that required to protect an isolated system. As such, impressed current systems are typically required for cathodic protection of existing UST systems.

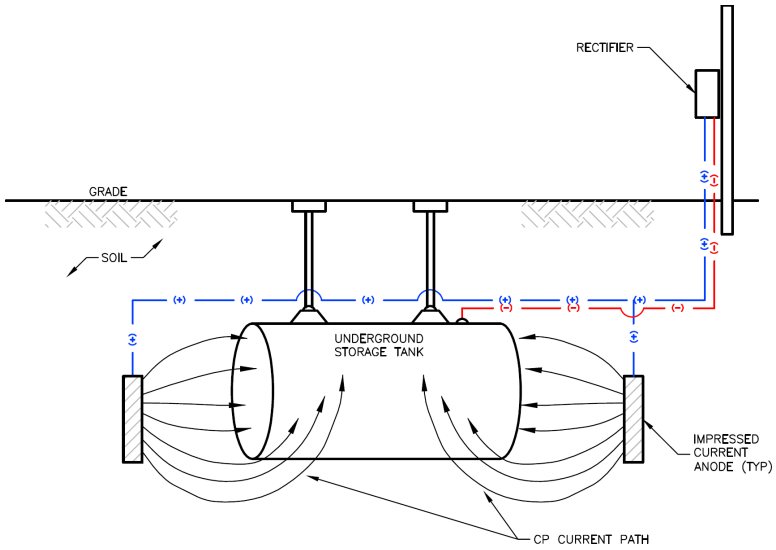


Figure 6-3
Impressed Current CP of an Underground Storage Tank

When cathodic protection current is applied through the soil to the UST system, metallic structures that are not continuous with the current return path may receive stray current interference and corrode at an accelerated rate. The zone of influence and severity of this condition is dependent on the relative location of the anode system with respect to the buried metallic structure, applied current from the CP system and voltage gradients that are developed from the anodes. Continuity testing should be performed upfront during the design phase and also during the construction phase as structures are uncovered during excavation. Most often, the tanks and piping at nuclear power plants are tied to station ground and therefore bonding is typically not necessary. However, certain structures may require more detailed testing to ensure that continuity was established. These structures may include cast iron and ductile iron pipes that are used for potable water, fire water, sanitary piping and concrete cylinder pipe. Corrugated metal storm drains, catch basins, pipe bollards and secondary fencing should also be evaluated for continuity. Resistance tests and voltage drop tests typically do not provide sufficient information to properly evaluate continuity of buried metallic structures. Continuity testing should consist of applying direct current from a temporary anode source, interrupting the current and measuring the structure-to-soil potential using a stationary reference electrode. The positive terminal of the voltmeter is then connected to the various structures under consideration and the On and Instant-Off structure-to-soil potentials are measured. If the potential is more electro-negative when current is applied then continuity is indicated. Conversely, if the potential is more electro-positive when current is applied then electrical discontinuity is indicated.

The flow of cathodic protection current from an external source through the electrolyte (soil) to the UST system will be accompanied by a potential difference between the earth and the structure, with the earth being positive (+) and the structure (–). To provide uniform current distribution to the tanks and piping a distributed anode systems is best suited for UST systems. The anodes may consist of pre-packaged canister anodes or bare anodes that are installed with coke breeze backfill. When designing a distributed anode system for a UST system the effective soil resistivity in which the anodes are to be placed should be known, so the anode-to-earth resistance can be calculated. For existing UST systems the anodes are placed vertically in the soil around the tank(s) and piping being protected. Dry or wet vacuum excavation methods may be

used to minimize damage to buried structures. If soil conditions permit, two or more anodes can be installed vertically in a hole to allow for higher current capacity. Care should be taken during installation of the anode system to ensure that no short circuits are present and resistance testing should be conducted as the anodes are placed. Ideally the individual cables from the anodes should terminate in a junction box, with a positive feed cable installed between the junction boxes and rectifier. Ideally all anode cables should extend to the rectifier or junction box without splices. Junction boxes should contain calibrated shunts to measure current flow to each anode. Alternatively, the anodes may be connected to a header cable using waterproof splice kits. Figure 6-4 provides a plan view of a distributed anode impressed current system for an underground DFO tank.

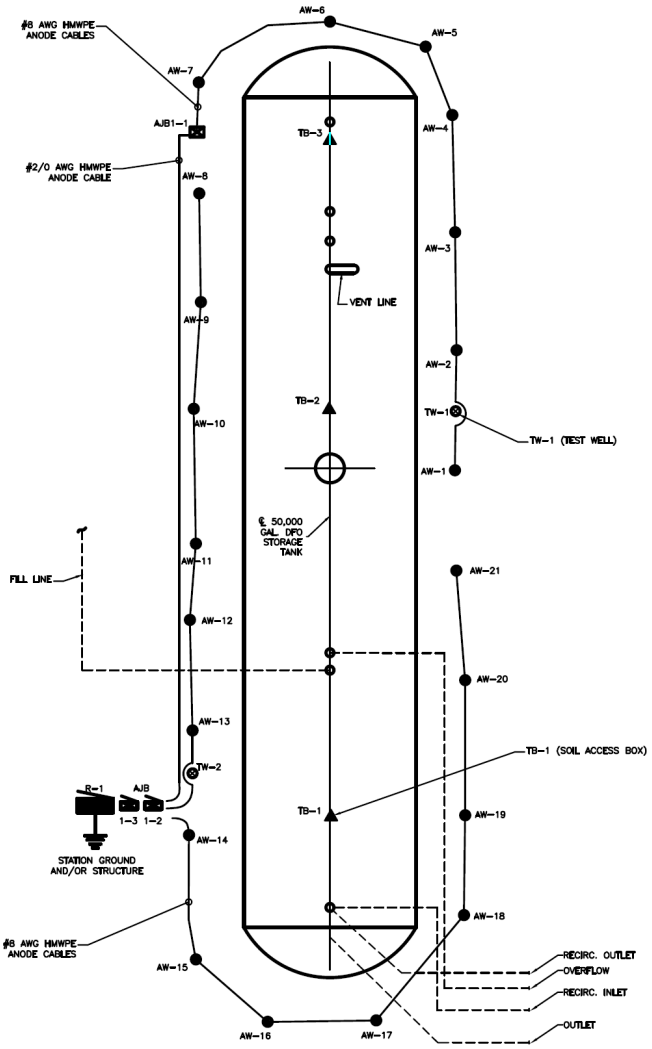


Figure 6-4
Plan View of a Distributed Anode Impressed Current System for a DFO Tank

Manufacturers produce rectifier units with a wide range of DC output and AC input ratings. Sufficient spare capacity should be provided in the rectifier output voltage to account for seasonal changes in the anode bed resistance. Rectifying elements should consist of silicon diodes, with upgraded lightning protection. DC output control may be provided by manual tap-switch adjustment. Various options are available for mounting the rectifier enclosure including

pole mount, floor mount and wall mount. Stainless steel cabinets and/or oil immersed enclosures should be considered where a highly corrosive atmosphere exists. If the rectifier and junction boxes are located in an area where combustible vapors are present from the fuel oil system then explosion proof cabinets and fittings should be specified. Since interruption of the rectifier DC output is required for measurement of the "Instant-Off" structure-to-electrolyte potential, synchronizing of the interruption cycle is necessary when multiple power supplies are installed in a given area. This can be accomplished by having an external connection for a portable interrupter hook-up or by having a global positioning system (GPS) synchronized current interrupter installed in the rectifier output. When an integral current interrupter is installed in the rectifier, a manual by-pass switch should be built into the rectifier to take the interrupter out of the circuit when not in use. Remote monitoring of the rectifier DC output may be considered if communication features are deemed suitable for plant security.

To eliminate unwanted excavation of the tank, system negative connections to the structure can be made to above ground piping or to station ground (i.e., No. 2/0 AWG bare copper conductor). Continuity checks should be made to ensure the proposed ground connection is electrically continuous with the UST system being protected. Cable connections should be made using the thermite welding or pin brazing methods, or by welding a steel tab to the structure for connection of the cable. To prevent moisture ingress, all structure negative connections should be coated with epoxy or other approved material.

6.2.4 CP of Internal Tank Bottoms

The internal surfaces of DFO tanks are usually coated with an epoxy liner to protect the metallic surface from corrosion. DFO tanks sometimes contain a residue of water which will typically collect at the base of the tank. Biocides may be added to the diesel fuel oil to reduce the potential for microbiologically induced corrosion (MIC). To provide for additional protection, flush mounted galvanic anodes (magnesium or zinc) may be bolted or welded to the tank bottom interior for corrosion control if water is present.

6.3 Operation and Maintenance

When designing a cathodic protection system for an underground storage tank, test stations are needed so the effectiveness of CP system can be consistently monitored. Portable reference electrodes placed at grade over the structure may be used for this purpose. Often soil access points (test boxes) are provided over the tanks so that the potential measurements are repeatedly taken at the same location. However the potential at grade may be a mixed potential that is dominated by the copper grounding. Ideally, permanent copper-copper sulfate reference electrodes should be installed at the base of the tank(s) or along the side of the tank(s) to measure the structure-to-soil potential. Alternately test wells, which consist of small diameter perforated PVC pipes, maybe installed along the side of the tank wall. The PVC pipe should be of sufficient diameter and length to facilitate measurement of the structure-to-soil potential using a portable reference electrode at the mid-point or base of the tank. Prior to taking a potential measurement, water is added to the test well and the portable reference electrode is lowered into the tube using a submersible adapter. Coupon test stations may also be incorporated into CP system design to

provide additional corrosion and cathodic protection system monitoring. NACE Standard RP0104 provides guidance in using coupons for CP system monitoring.[20]

The polarized -850 mV (CSE) criterion is the most commonly used criteria for cathodic protection of buried and submerged metallic structures and is one of three identified for steel and cast iron piping referenced in NACE SP0169. This criterion states that adequate protection is achieved when a negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode is achieved. The polarized potential can be defined as the potential across the structure/electrolyte interface that is the sum of the corrosion potential (E_{corr}) and the cathodic polarization. The polarized potential is measured directly after interruption of all current sources and is often referred to as the "Off" or "Instant-Off" potential.

Guidelines regarding monitoring and maintenance of CP systems can be found in NACE SP0169 and RP0285. As a minimum the DC output of the cathodic protection rectifiers should be checked every 2 months and any deficiencies to the CP systems corrected in a timely manner. The effectiveness of the CP systems should be evaluated annually. Annual surveys may consist of anode junction box current readings and the measurement of polarized instant-off structure-to-soil potential at the test stations. In conjunction with the monitoring and maintenance program, plant electricians should be trained to provide the basic monitoring and testing services for the CP system. Training sessions should include corrosion and cathodic protection theory, record keeping, rectifier trouble shooting and procedures for measuring rectifier voltage, current and structure-to-electrolyte potential.

[20] NACE RP0104-2004 "The Use of Coupons for Cathodic Protection Monitoring Applications," NACE International, Houston, TX.

7
CP OF ABOVE GROUND STORAGE TANKS

It is important, both economically and environmentally, to protect above ground storage tank (AST) bottoms from corrosion. A release of product from an above ground storage tank can be costly and environmentally sensitive. Whether the tank bottom is the initial bottom of a new tank, a replacement bottom, or a double bottom, proper corrosion protection is important.

The area under the tank bottom can become moist and remain moist from groundwater, under-tank condensation or seam leakage. In the past, replacement bottoms were installed over the old tank bottom and welded to the existing tank wall. This procedure will allow a corrosion cell to form by making the new steel anodic to the old tank bottom, and in the process accelerating corrosion of the new steel tank bottom surface. In many locations cathodic protection is mandated by local regulations for tanks storing hydro-carbons or hazardous materials.

7.1 Cathodic Protection

Cathodic protection can be applied to protect new or existing tank bottoms, but cannot protect carbon steel surfaces that are not in direct contact with an electrolyte. CP has been applied to ASTs using a variety of approaches with varying degrees of success. The use of sacrificial anodes is typically limited to those applications where the tanks are relatively small in diameter and where the metallic surface that is exposed to the electrolyte is minimized through the application of a dielectric coating. Impressed current systems have been used where more protective current is required and where a longer life system is desired. API 651[21] and NACE RP0193 provide guidelines regarding the design, installation and maintenance of CP systems for exterior tank bottoms of on-grade carbon steel storage tanks.

When designing a cathodic protection system for an AST, the design engineer should obtain the following information:

- Tank Diameter: This is necessary to calculate the surface area to be protected.
- Tank Bottom Coating: Typically tank bottoms are bare plate steel, but in some cases the plate steel may be coated on the bottom, which reduces the current required for cathodic protection. Depending on the temperature of the product, a design current density of 1 mA/ft^2 (10 mA/m^2) is usually sufficient to achieve NACE criteria for cathodic protection.
- Depth of Anode: The separation distance between the anode and the tank bottom affects current spread and anode spacing.
- Sand/Soil Resistivity: This information is necessary to estimate overall system resistance necessary to properly size the rectifier voltage.

[21] API Recommended Practice 651, "Cathodic Protection of Above-Ground Petroleum Storage Tanks", Third Edition, January 1, 2007, American Petroleum Institute, Washington, DC.

- Tank Operating Temperature: Corrosion rates can significantly increase with elevated temperature, necessitating additional current demand. A temperature correction is typically a 25% increase in current demand for every 10°C above 30°C.
- Area Classification: Rectifiers and junction boxes must be designed with suitable enclosures for the area classification where they will be installed.
- Secondary Containment Liners: If polyethylene or other such plastic liners are to be placed underneath the tank, these liners act as a barrier to the flow of current and the anodes must be placed between the liner and the tank bottom.



Key Technical Point

Depending on the temperature of the product, a design current density of 1 mA/ft2 (10 mA/m2) is usually sufficient to achieve NACE criteria for cathodic protection.

7.2 Existing Tanks

Several different types of impressed current anode installations have been used to distribute the protective current to the tank bottom. However, when the design of the tank uses a containment liner that shields the CP current from the tank bottom (i.e. polyethylene liner), these methods of anode installation cannot be used.



Key Technical Point

Several different types of impressed current anode installations have been used to distribute the protective current to the tank bottom. However, when the design of the tank uses a containment liner that shields the CP current from the tank bottom (i.e. polyethylene liner), these methods of anode installation cannot be used.

7.2.1 Shallow Distributed Anodes around Tank Periphery

Figure 7-1 provides an example of horizontal or vertical anodes that are distributed around the periphery of the AST. These anodes are typically augured to depths of 5-10 feet (15-30 m). For this type of design, the critical issue is assuring that sufficient current reaches the center of the tank. AST bottoms are large bare surfaces that require a significant amount of current. To assure that current distributes properly, the anode depth and distance from the tank is critical. Often, shallow peripheral anodes are not able to throw current to the center of the tank and in general shallow distributed anodes that are installed around the periphery of the tank are not recommended for ASTs exceeding 20 ft (6 m).

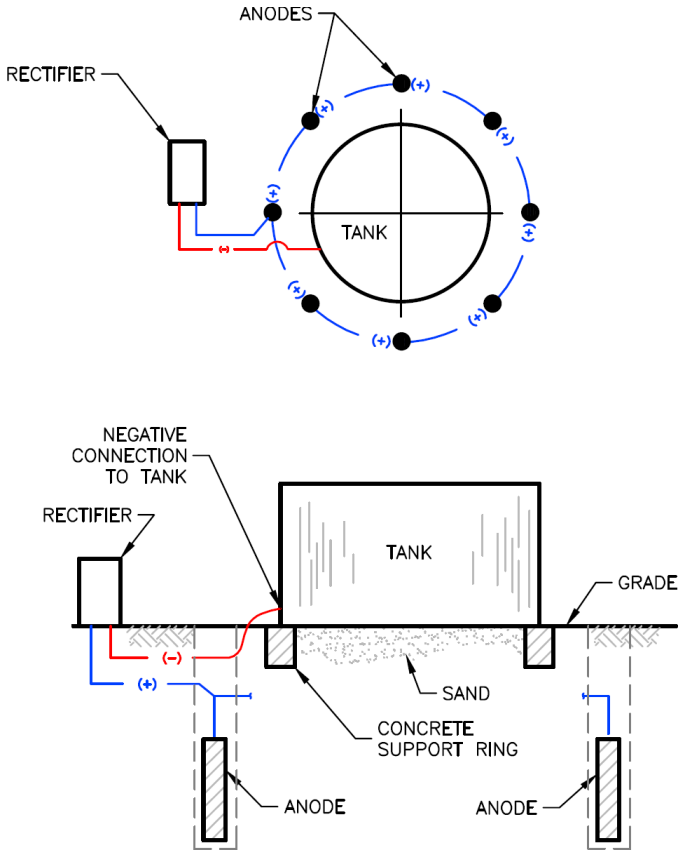


Figure 7-1
Distributed Anode Impressed Current System for an AST

7.2.2 Deep Anode Systems

This approach is based on using one or more deep anode systems located well below the tank bottom to provide current uniformly to the tank bottom (Figure 7-2). This approach has some limitations in heavily congested plant environments where current can flow to other buried structures. When multiple deep anodes are employed to protect more than one tank in a cluster, care must be taken to assure proper current distribution. As with any deep well, there are concerns with drilling deep in the ground, which include access issues for the drill rig, environmental concerns, permitting and handling of drilling spoils. Even with the deep well approach reference electrodes should be installed under each tank.

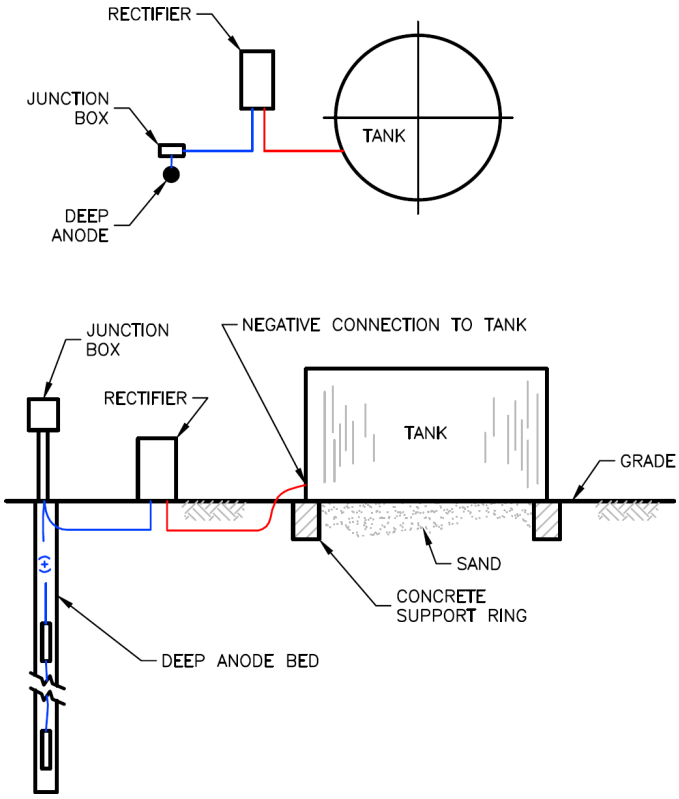


Figure 7-2
Deep Anode Impressed Current System for an AST

7.2.3 Angle Drilled Anode Systems

The angle drilled anode method, which extends the anode beneath the tank bottom, is probably the best system from a current distribution standpoint for existing ASTs (Figure 7-3). The system is similar to a peripheral anode system, except that the anodes are installed in holes that are drilled at a nominal 45º angle beneath the tank. This type of system distributes the current to the center of the tank bottom and overcomes the tendency for most of the current to flow to the tank perimeter. A PVC pipe with the lower portion perforated is used to facilitate the anode and coke breeze installation. Often horizontal directional drilling (HDD) equipment is used for this method of installation.

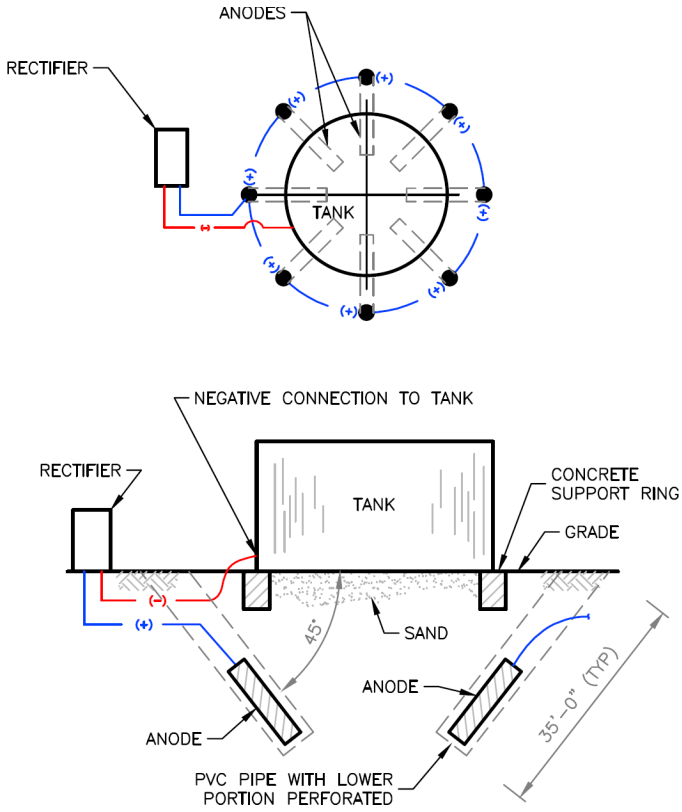


Figure 7-3
Angle Drilled Anode System for an AST

7.3 New Construction

For new construction without secondary containment, conventional cathodic protection anodes can be installed under the tank bottom to optimize the distribution of the CP current. Additionally, it is recommended that permanent reference electrodes be placed at the center of the tank to provide accurate system adjustment and monitoring.

Many new tanks are now constructed with secondary containment liners typically made of 60 mils thick high density polyethylene (HDPE) installed 6-12 inches under the tank bottom. A complementary anode design consists of using a mixed metal oxide (MMO) titanium ribbon to form a grid. The ribbon is linearly extended in strips above the secondary containment liner and titanium conductor bars are resistance welded perpendicular to the ribbon to form an anode grid (Figure 7-4). The grid evenly distributes current to the tank bottom through multiple power feeds. It can be placed as close as 4 inches from the tank bottom and still maintain proper protection levels. This design using MMO anodes can satisfy design life requirements up to 50 years. A platinized niobium linear anode system has also been provided using parallel segments and concentric ring designs.

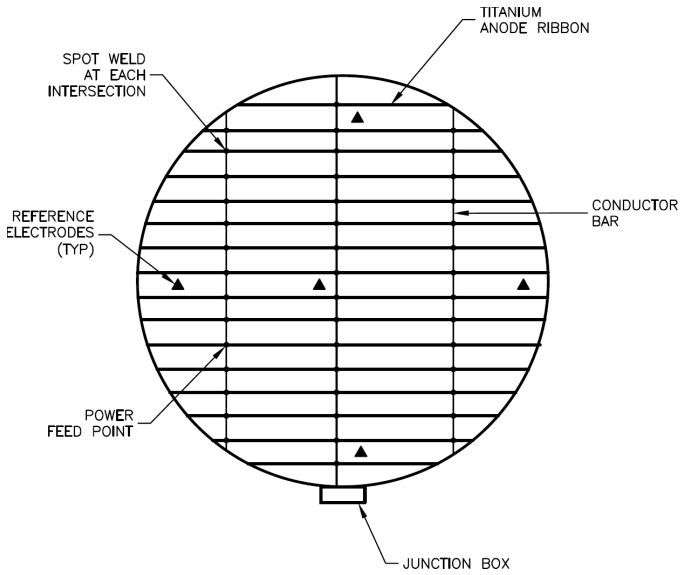


Figure 7-4
Titanium Anode Grid System for an AST

7.4 Operation and Maintenance

The problem associated with monitoring cathodic protection systems on tank bottoms is the inability to place a portable reference electrode in close proximity to the underside of the tank. The placement of the reference electrode at the tank rim may yield erroneous results because of potential gradients created in the soil as a result of the current discharge from the anode. This is particularly true when using distributed anodes installed along the periphery of the tank. In certain cases, it has been determined that potential measurements at the perimeter only provide information on the CP being applied near the rim. As the reference cell is advanced towards the center of the tank, the potentials become more positive to the point where little if any potential shift is measured; thus indicating a lack of effective corrosion protection at the center. For 120 foot diameter tanks protected by distributed or deep anode systems, it is not unusual for the potential at the center of the tank to be on the order of 300 millivolts less negative than at the tank rim. However, the angle drilled application method overcomes this problem by evenly distributing the current along the tank bottom.

Potential measurements at the center of the tank and at other areas under the tank are necessary if tank bottom cathodic protection levels are to be accurately evaluated. This can be accomplished by boring perforated pipe under the tank for reference cell access. When testing, the liquid level of the tank must be sufficiently high to create intimate contact between the tank bottom and the pad (electrolyte). The polarized -850 mV (CSE) criterion is the most commonly used criteria for cathodic protection of buried and submerged metallic structures and is one of three identified in NACE RP0193. This criterion states that adequate protection is achieved when a negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode is achieved. The polarized potential can be defined as the potential across the structure/electrolyte interface that is the sum of the corrosion potential (Ecorr) and the cathodic polarization. The polarized potential is measured directly after interruption of all current sources and is often referred to as the “Off” or “Instant-Off” potential.

Guidelines regarding monitoring and maintenance of CP systems can be found in NACE SP0169 and RP0193. As a minimum the DC output of the cathodic protection rectifiers should be measured every 2 month and any deficiencies to the CP systems should be corrected in a timely manner. The effectiveness of the CP systems should be evaluated annually. Annual surveys may consist of anode junction box current readings and the measurement of polarized instant-off structure-to-soil potential using permanently installed reference electrodes installed beneath the tank bottom or by measuring the potential of the tank bottom using a portable reference cell that is drawn through a reference tube that extends across the bottom of the tank. In conjunction with the monitoring and maintenance program, plant electricians should be trained to provide the basic monitoring and testing services for the CP system. Training sessions should include corrosion and cathodic protection theory, record keeping, rectifier trouble shooting and procedures for measuring rectifier voltage, current and structure-to-electrolyte potential.

8
CP OF METEOROLOGICAL TOWER GUY ANCHORS

The steel guy anchors of meteorological (MET) towers are typically galvanized using the hot dipped galvanizing process for corrosion protection. From a corrosion control standpoint this is advantageous, as the zinc layer acts as an anode to the steel shaft and will consume (corrode) in favor of the steel substrate. However, the galvanizing may provide a false sense of security because of the satisfactory appearance of the galvanizing above grade. In the below grade section concentrated corrosion may be evident in the area immediately below the air/ground interface, especially if the shaft is subject to wet conditions. If corrosion is significant, loss of section in the guy steel anchor could result in structural failure of the tower. Cathodic protection, both galvanic and impressed current systems, can be used to mitigate and control corrosion of these guy anchors.

8.1 Corrosion Mechanism

Epoxy coatings are also often used to protect the steel guy anchors. This is accomplished by coating the entire shaft with an epoxy that acts as an insulator to protect the steel from direct exposure to the electrolyte. This method is beneficial in protecting the steel shafts against corrosion. However, it has been proven that even the best epoxy coatings cannot guarantee 100% isolation of the substrate from the electrolyte. In addition, the coating can be damaged during shipping or installation, leaving small anomalies or "holidays" in the coating. Furthermore the anchor shafts are often grounded for lightning protection. The grounding may consist of a ring of bare copper conductors and copper ground rods around the base of each anchor. The steel will be anodic and corrode with respect to the copper (cathode). Concentrated galvanic corrosion can then occur at the holidays in the epoxy coating due to the dissimilar metal coupling and small anode / large cathode area ratio effect. The shaft is open to accelerated corrosion in the smaller areas that are exposed to the electrolyte, which rapidly become larger. This type of concentration cell is worse than if the shaft were left uncoated and allowed to corrode more evenly on its entire surface.

The most common anchor design is one in which the entire anchor shaft is encased in concrete. This design is sometimes used for its structural capacity, but it also has its corrosion control advantages. The greatest advantage is that the steel shaft is encased in a highly alkaline concrete. The concrete may also have a higher resistivity than the surrounding soil and therefore the corrosion currents will be substantially reduced. In addition, if the shaft is entirely encased there is no anode/cathode relationship on the shaft itself. The disadvantage to this method is the possibility that the concrete could become cracked or delaminated. If this should happen and water or soil fills the cracks, a corrosion cell is created. The anode is the area of the steel shaft inside the cracks exposed to the water or soil, and the cathode is the portion of the shaft inside the un-cracked concrete. Furthermore if the concrete anchor block is entirely below grade, a corrosion cell could develop on the anchor shaft at the interface between soil layers and also at the interface between the soil and concrete. Figure 8-1 illustrates how various soil types and electrolytes can create a concentration corrosion cell on a tower shaft anchor. The portion of the

shaft in contact with the lower resistivity clay soil will corrode with respect to the portion of the shaft in the higher resistivity concrete and loose gravely soil.

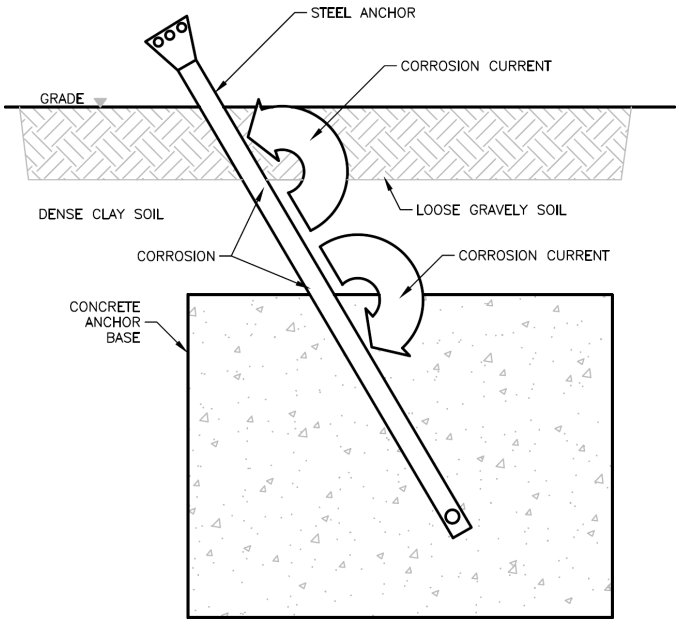


Figure 8-1
Corrosion of Steel Anchor Shaft by Differences in Electrolyte

8.2 Cathodic Protection

Figure 8-2 illustrates the application of galvanic anode cathodic protection to a typical anchor support. The anchor support without cathodic protection installed is anodic to the copper grounding system and the portion of the shaft inside the concrete. By electrically bonding sacrificial anodes to the anchor support, the current flows away from the sacrificial anode and toward the anchor shaft and copper ground rod. It then returns through the electrical path. In this way, the elements of the corrosion cell have been used to make the anchor shaft the cathode, thereby eliminating or mitigating corrosion.

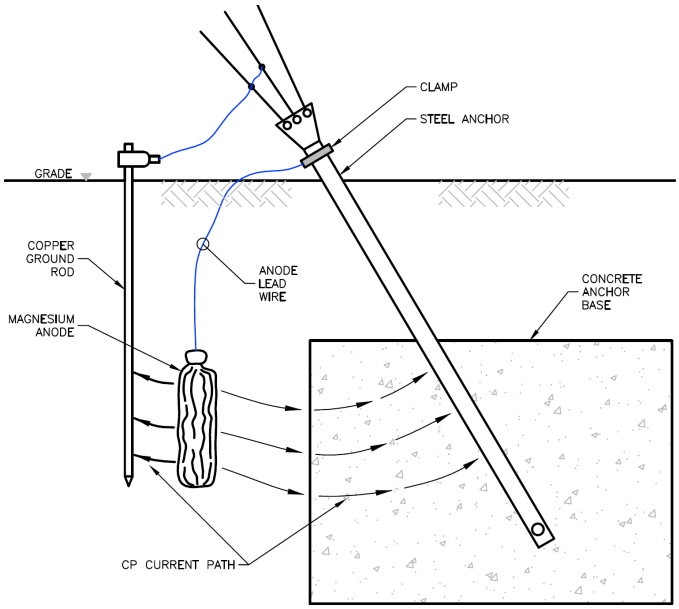


Figure 8-2
Galvanic Anode CP of a Steel Anchor Shaft

Sacrificial anodes vary widely in their sizes, shapes and make-up. Galvanic anodes for soil applications are typically made of magnesium or zinc. The 17-lb high potential magnesium anode is one of the most commonly used anodes for buried structures. The galvanic anode is usually placed in a cotton bag surrounded by a gypsum, bentonite and sodium sulfate mixture. This mixture assists in the activation of the current flow and to ensure that moisture remains around the area of the anode. A wire is attached to the inner core of the anode and the anode wire is electrically connected to the steel anchor. Attachment of the wire is usually made to the above grade portion of the guy anchor using a beam clamp. This will allow the anode wire to be easily disconnected for purposes of routine testing.

Because of the grounding requirement for lightning protection, the performance of the galvanic anode system could be adversely affected by any additional buried components such as copper ground rods, copper ground conductors, metal fencing and steel reinforcement in building foundations, etc. that are electrically bonded to the anchor rods. In order for the galvanic anode system to provide effective protection to the guy anchors and meet the desired service life, it is important to take into account the additional surface area of buried structures that are electrically bonded to the tower. Often, more than one anode is required for each anchor to provide adequate protection.

Key Technical Point

In order for the galvanic anode system to provide effective protection to the guy anchors and meet the desired service life, it is important to take into account the additional surface area of buried structures that are electrically bonded to the tower.

An impressed current system will provide a higher level of cathodic protection to the anchors as compared to a galvanic anode system. A higher current demand may be required for protection of the anchors as a result of the copper grounding. Anodes may be distributed around the tower and direct current is impressed through the soil and onto the buried portion of the steel anchors by means of a rectifier. Figure 8-3 illustrates a typical application of this system at a MET tower site. An advantage of impressed current cathodic protection is that the entire system can be centrally located near the base of the tower. The tower and its guy cables are the electrical connections to the anchor supports, provided that the guy cables do not have cable insulators. The anodes are placed strategically in the same central location. The rectifier is then mounted on the transmitter building or anywhere AC power is readily accessed.

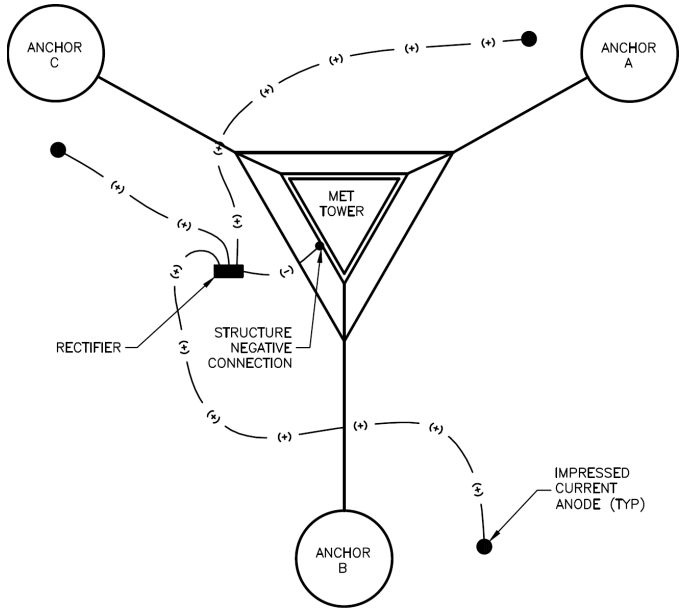


Figure 8-3
Impressed Current CP of Steel Anchor Shafts at a MET Tower

8.3 Operation and Maintenance

The effectiveness of the system should be evaluated by placing a portable copper-copper sulfate reference electrode in the soil at grade near the anchor and measuring the structure-to-soil potential. Alternatively, permanent copper-copper sulfate reference electrodes should be installed at the base of the anchor to measure the structure-to-soil potential. The reference electrode lead wire may be brought up into a test station that is mounted at the base of the guy wire.

The polarized -850 mV (CSE) criterion is the most commonly used criteria for cathodic protection of buried and submerged metallic structures and is one of three identified for steel and cast iron piping referenced in NACE SP0169. This criterion states that adequate protection is achieved when a negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode is achieved. The polarized potential can be defined as the potential across the structure/electrolyte interface that is the sum of the corrosion potential (Ecorr) and the cathodic polarization. The polarized potential is measured directly after interruption of all current sources and is often referred to as the “Off” or “Instant-Off” potential.

Guidelines regarding monitoring and maintenance of CP systems can be found in NACE SP0169. As a minimum the DC output of the cathodic protection rectifiers should be checked every 2 months and any deficiencies to the CP systems should be corrected in a timely manner. The effectiveness of the CP systems should be evaluated annually. Annual surveys may consist of anode current measurements and the measurement of polarized instant-off structure-to-soil potential at each anchor shaft. In conjunction with the monitoring and maintenance program, plant electricians should be trained to provide the basic monitoring and testing services for the CP system. Training sessions should include corrosion and cathodic protection theory, record keeping, rectifier trouble shooting and procedures for measuring rectifier voltage, current and structure-to-electrolyte potential.

9
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A
GLOSSARY

Activation. The changing of a passive surface of a metal to a chemically active state

Active. A state in which a metal tends to corrode with respect to standard hydrogen electrode potential.

Absorption. The surface retention of liquid, gas molecules, atoms, or ions by a solid.

Aeration Cell. An electrolytic cell resulting from differences in dissolved oxygen at two points.

Amphoteric Material. An amphoteric (or amphinprotic) material is one that can display both acidic and basic properties. The term is most commonly applied to the oxides and hydroxides of metals that can form both cations and complex anions. For example, zinc oxide dissolves in acids to form zinc salts and also dissolves in alkalis to form zincates, $[Zn(OH)_4]^{2-}$.

Anion. An ion or radical, which is attracted to the anode because of the negative charge.

Anode. An electrode from which, ions and/or electrons migrate towards cathode through the electrolyte and to which, electrons flow through an external conductor.

Anode corrosion efficiency. The ratio of actual to theoretical corrosion based on the total current flow. It is calculated by Faraday's law from the quantity of electricity that has passed.

Anode effect. The effect produced by polarization of the anode in electrolysis e.g., by a gas film.

Anodic inhibitor. A chemical substance that prevents or reduces the rate of the anodic or oxidation reaction by a physical or chemical action.

Anodic reaction. Electrode reaction to produce electrons.

Atmospheric corrosion. The gradual degradation of a material by contact with the contents of the atmosphere, such as oxygen, water vapor, and salts.

Backfill. Material placed in the space around anodes or in the trench around the pipe.

Bimetallic corrosion. (Galvanic Corrosion) Corrosion resulting by contact from dissimilar metal contact.

Biological corrosion. Deterioration of metals as a result of the metabolic activity of microorganisms.

Bituminous coating. Coal tar or asphalt-based coating.

Blister. A raised area on the surface of a coating resulting from the loss of adhesion between a coating and the base metal.

Buried Piping. Pipe that is below grade and in direct contact with soil or concrete.

Calcareous coating or deposit. A layer consisting of a mixture of calcium carbonate and magnesium hydroxide deposited on surfaces being cathodically protected because of the increased pH adjacent to the protected surface.

Calomel electrode. A reference electrode used in the measurement of the potentials of other electrodes.

Cathode efficiency. Current efficiency at the cathode.

Cathode. The electrode of an electrolytic cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic corrosion. Corrosion resulting from a cathodic condition of a structure usually caused by the reaction of an amphoteric metal with the alkaline products of electrolysis.

Cathodic disbondment. The destruction of adhesion between a coating and its substrate by products of a cathodic reaction.

Cathodic inhibitor. A chemical substance or mixture that prevents or reduces the rate of the cathodic or reduction reaction by physical or chemical action.

Cathodic polarization. Change of the electrode potential in the active (negative) direction due to current flow.

Cathodic protection. Reduction of corrosion rate by shifting the corrosion potential of the electrode toward a less oxidizing potential by applying an external electromotive force.

Cathodic reaction. Electrode reaction equivalent to a transfer of negative charge from the electronic to the ionic conductor. A cathodic reaction is a reduction process.

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

Cell. See electrochemical cell.

Concentration cell. An electrolytic cell, the electromotive force is caused by a difference in concentration of some component in the electrolyte. This difference leads to the formation of discrete cathode and anode regions.

Concentration polarization. That portion of the polarization of a cell produced by concentration changes resulting from passage of' current through the electrolyte.

Conductivity. The ratio of the electric current density to the electric field in a material. Also called electrical conductivity or specific conductance.

Contact corrosion. A term primarily used in Europe to describe galvanic corrosion between dissimilar metals.

Contact potential. The potential difference at the junction of two dissimilar substances.

Continuity bond. A metallic connection that provides electrical continuity between two metal structures.

Corrosion. The deterioration of a material, usually a metal, due reaction (oxidation) with its environment.

Corrosion rate. Corrosion effect on a metal per unit of time.

Covalent. The ability to form a bond in which two atoms share electrons.

Current density. The current per unit area.

Deep groundbed. One or more anodes installed vertically at a nominal depth of 15 m (50 ft) or more below the earth's surface in a drilled hole for the purpose of supplying cathodic protection for an underground or submerged metallic structure.

Delamination. Breaking away or separation of composite materials into layers. Reinforced concrete structures may crack or delaminate as a result of the volumetric increase from the rebar corrosion product.

Depolarization. A decrease in the polarization of an electrode; the elimination or reduction of polarization by physical or chemical means. Depolarization results in increased corrosion.

Dielectric shield. In a cathodic protection system, an electrically nonconductive material, such as a coating, plastic sheet or pipe that is placed between the protected structure and an adjacent unprotected structure to avoid current wastage and to improve current distribution.

Differential aeration cell. An electrolytic cell in which the electromotive force has caused a difference in oxygen concentration at one electrode compared with that at another electrode of the same material.

Disbondment. The destruction of adhesion between a coating and the surface coated.

Electrical isolation. The condition of being electrically separated from other metallic structures.

Electrochemical cell. An electrochemical system consisting of an anode and a cathode in metallic contact and immersed in an electrolyte.

Electrochemical corrosion. Corrosion accompanied by a flow of electrons between cathodic and anodic areas on metallic surfaces.

Electrochemical potential. The potential of an electrode in an electrolyte relative to a reference electrode measured under open circuit conditions.

Electrode polarization. Change of electrode potential with respect to a reference value.

Electrode potential. The potential of an electrode as measured against a reference electrode.

Electrode. A conductor used to establish electrical contact with an electrolytic part of an electrochemical cell

Electrolysis. Production of chemical changes of the electrolyte by the passage of current through an electrochemical cell.

Electrolyte. A chemical substance or mixture, usually liquid, containing ions that migrate in an electric field.

Environment. The surroundings or conditions (physical, chemical, mechanical) in which a material exists.

Faraday's law. (1) The amount of any substance dissolved or deposited in electrolysis is proportional to the total electric charge passed. (2) The amounts of different substances dissolved

or deposited by the passage of the same electric charge are proportional to their equivalent weights.

Foreign structure. Any metallic structure that is not an intended part of a cathodic protection system.

Galvanic anode. A metal that, because of its relative position in the galvanic series, provides sacrificial protection to the structure when it is coupled in an electrolyte.

Galvanic cell. A cell in which chemical change is the source of electrical energy.

Galvanic corrosion. Corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

Galvanic current. The electric current that flows between metals or conductive nonmetal in a galvanic couple.

Galvanic series. A list of metals and alloys arranged according to their relative potentials in a given environment.

General corrosion. A form of deterioration that is distributed more or less uniformly over a surface.

Groundbed. A buried anode in the cathodic protection of pipelines or other buried structures.

Half cell. See Reference Electrode.

Holiday. A discontinuity of coating that exposes the metal surface to the environment.

Impressed current. Direct current supplied by a device employing a power source external to the electrodes of a cathodic protection system.

Industrial atmosphere. An atmosphere in an area of heavy industry with soot, fly ash, and sulfur compounds as the principal constituents.

Inert anode. An anode that is insoluble in the electrolyte under the conditions prevailing in the electrolysis.

Inhibitor. A chemical substance, when present in the environment, prevents or reduces corrosion.

Ion. An atom, or group of atoms, that has gained or lost one or more outer electrons and thus carries an electric charge. Positive ions, or cations, are deficient in outer electrons. Negative ions, or anions, have an excess of outer electrons.

Isolation. See Electrical Isolation.

Limiting current density. The maximum current density that can be used to obtain a desired electrode reaction without undue interference such as from polarization.

Line current. The direct current flowing on a pipeline**.**

Local action. Corrosion due to the action of "local cells," that is, galvanic cells resulting from adjacent non-homogeneous areas on a metal surface exposed to an electrolyte.

Local cell. A galvanic cell resulting from adjacent non-homogeneous areas on a metal surface in an electrolyte.

Metal ion concentration cell. A galvanic cell caused by a difference in metal ion concentration at two locations on the same metal surface.

Noble metal. A metal whose potential is highly positive relative to the hydrogen electrode.

Open-circuit potential. The potential of an electrode measured with respect to a reference electrode or another electrode when no current flows to or from it.

Oxidation. Change in the state of the atoms or ions of an element to a higher positive state by the loss of electrons. An oxidizing agent is an element that can remove electrons to another element.

Oxidation. A corrosion reaction in which the corroded metal forms an oxide

Passivation. The process in metal corrosion by which metals become passive.

Polarization. Polarization is the change of potential of a metal surface resulting from the passage of current directly to or from an electrolyte.

Potential. Voltage difference between two materials. Potential is the driving influence of an electrochemical reaction.

Reduction. A reaction in which there is a decrease in valence resulting from a gain in electrons. Contrast with oxidation.

Reference electrode. A non-polarizing electrode with a known and highly reproducible potential used for potentiometric analyses.

Sacrificial protection. The reduction or prevention of corrosion of a metal in an electrolyte by a galvanic coupling to a more anodic metal.

Standard electrode potential. The reversible potential for an electrode process when all products and reactions are at unit activity on a scale in which the potential for the standard hydrogen half-cell is zero.

Stray current. The current flowing through paths other than the intended circuit.

Stray current corrosion. The corrosion resulting from direct-current flow through paths other than the intended circuit.

Voids. A term generally applied to paints to describe holidays, holes, and skips in a coating. Also used to describe shrinkage in castings and weld.

B
CATHODIC PROTECTION REFERENCES

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C
CATHODIC PROTECTION PREVENTIVE MAINTENANCE TASKS

The purpose of a monitoring and maintenance program is to ensure the effectiveness of the CP system throughout the life of the structure. As such, electrical measurements and inspection are necessary to ensure protection levels have been established in accordance with applicable CP criteria and that each part of the CP system is operating properly. Conditions that effect protection levels are subject to change. Periodic measurements and inspections are necessary to detect changes in the CP system.

All rectifiers operating impressed current systems should be checked at two (2) month intervals. Longer or shorter intervals may be appropriate. Evidence of proper functioning may include measurement of the rectifier DC output voltage and current, a signal (status lamp) indicating that the direct current output is within a preselected range consistent with normal operation of the CP system, or measurement of satisfactory CP levels on the structure. Remote monitoring of the rectifier DC output may be used to help facilitate this effort.

All impressed current CP systems should be inspected annually as part of a preventative maintenance program to minimize in-service failure. Longer or shorter intervals may be appropriate. Rectifier inspections may include a check for electrical malfunctions, safety ground connections, meter accuracy, efficiency and circuit resistance. The annual inspection should include measurement of the polarized (instant-off) structure-to-soil potential at test stations and other monitoring sites using portable and/or permanently installed reference electrodes, anode currents at junction boxes, and rectifier DC output voltage and current readings.

All galvanic anode CP systems should be inspected annually as part of a preventative maintenance program to minimize in-service failure. Longer or shorter intervals may be appropriate. Where appropriate, the inspection should include measurement of the structure-to-electrolyte potential at test stations and/or test sites, measurement of the galvanic anode current, visual inspection of the anode for consumption/deterioration and verification that isolation joints and DC de-coupling devices are effective.

Table C-1 contains the recommended maintenance intervals for impressed current systems:

Table C-1
Recommended Maintenance Program for Impressed Current System

Task	Frequency
Corrosion Survey	• 30 days after a major modification to the protected structure or to the cathodic protection system. • Annually • After any inspection that necessitates a corrosion survey
Rectifier Inspection	• At 2 month intervals

The recommended maintenance program for a galvanic anode system is shown in Table C-2. The frequency of the testing is typically yearly, although more frequent measurements provide a better database for trending purposes.

Table C-2
Recommended Maintenance Program for a Galvanic Anode System

Task	Frequency
Corrosion Survey	• 30 days after a major modification to the protected structure or to the cathodic protection system • Annually • After any inspection that necessitates a corrosion survey

D
LISTING OF KEY POINTS

The primary intent of the key technical points is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these pop outs was selected by the EPRI Project Manager, TAG members, and the consultant that prepared this guide.

The pop outs are organized according to three categories: Operation and Maintenance (O&M) Cost, Technical, and Human Performance. Each category has an identifying icon, as shown below, to draw attention to it when quickly reviewing the guide.



Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.



Key Technical Point

Targets information that will lead to improved equipment reliability.



Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or to ease completion of the task.

The following is a summary of the key points in this report by category. The listing restates each key point and provides reference to its location in the body of the report. By reviewing this listing, users of this guide can determine whether they have taken advantage of key information that the writers of the guide believe would benefit their plants.

D.1 Key O&M Cost Points



Key O&M Cost Point: Section 1 - Introduction

Cathodic protection is essential to maintaining any metallic structure in a corrosive environment at the lowest life cycle cost.

D.2 Key Technical Points



Key Technical Point: Section 2 - CP of Condensers and Heat Exchangers

Because of the high current demand that is required for protection of these units and the relatively short life of galvanic anodes, the impressed current method is usually the preferred approach for cathodic protection of surface condensers and heat exchangers.



Key Technical Point: Section 2, 2.1 – CP of Condensers and Heat Exchangers, Corrosion Mechanism

The primary factors affecting galvanic corrosion in condensers and heat exchangers include the electrochemical characteristics; that is the potential and polarization of the different alloys, the effective area relationships of the different alloys, and the specific characteristics of the cooling water (i.e., conductivity, temperature, oxygen content and velocity).



Key Technical Point: Section 2, 2.2 – CP of Condensers and Heat Exchangers, Cathodic Protection

Cathodic protection can be used to mitigate galvanic corrosion of the tubesheet and waterbox, as well as retard inlet end erosion/corrosion of the tubes. Current densities for CP of these structures typically range from 50-200 mA/ft^2 (~0.5-2.0 A/m^2).



Key Technical Point: Section 2, 2.2 – CP of Condensers and Heat Exchangers, Cathodic Protection

In general for a surface condenser the sacrificial anode type system becomes impractical at high levels of current exceeding 50 Amps. It is not uncommon for a typical current demand of an impressed current system to exceed 200 Amps per condenser.



Key Technical Point: Section 3, 3.1 – CP of Atmospheric Exposed Reinforced Concrete Structures, Corrosion Mechanism

Chlorides are the most common source of contamination that lead to corrosion of the reinforcing steel in concrete.



Key Technical Point: Section 3, 3.2 – CP of Atmospheric Exposed Reinforced Concrete Structures, Galvanic Anode Systems

The current that is produced by the galvanic anode is a function of the environment (i.e., moisture and temperature conditions) and the output cannot be easily adjusted or controlled as with an impressed current CP system.



Key Technical Point: Section 3, 3.3 – CP of Atmospheric Exposed Reinforced Concrete Structures, Impressed Current CP Systems

Current densities for cathodic protection of existing reinforced concrete may range between 0.1 and 1.0 mA/ft2 (1.0 and 10 mA/m2) depending on the environment and degree of rebar corrosion.



Key Technical Point: Section 4, 4.1 – CP of Intake Structures, Corrosion Mechanism

The corrosion problems encountered for the materials which comprise an intake structure are primarily associated with the coupling of dissimilar metals exposed to a corrosive environment.



Key Technical Point: Section 4, 4.2 – CP of Intake Structures, Cathodic Protection

As in the case of condenser water boxes, the impressed current cathodic protection system is usually the preferred approach for effective corrosion control of traveling screens and trash racks. Galvanic anode systems often require a large volume of anode material to provide a sufficient amount of current to achieve protection and maintain a reasonable cathodic protection system life.



Key Technical Point: Section 5, 5.1 – CP of Steel Piling in Soil, Corrosion Mechanism

The position of the water table with respect to the steel pile is probably the most important factor affecting corrosion of steel piling in soil, as little corrosion has been found on piling below the water table.



Key Technical Point: Section 5, 5.2 – CP of Steel Piling in Soil, Cathodic Protection

Cathodic protection of steel piling in soil is almost always accomplished using the impressed current method. This is because of the significant current that is required to protect the extensive area of bare metal surface.



Key Technical Point: Section 6, 6.1 – CP of Underground Storage Tanks, Corrosion Mechanism

Underground storage tanks are almost always subject to oxygen cell attack, especially when placed under pavement. Areas with lower oxygen concentration become anodic and corrode with respect to areas of higher oxygen concentration (cathode).



Key Technical Point: Section 6, 6.2, 6.2.2 – CP of Underground Storage Tanks, Cathodic Protection, CP of New UST Systems

Factory-fabricated system galvanic anode systems are available for new USTs. The protection system consists of three basic parts: a) a coating with high di-electrical qualities, b) electrically isolated fittings, and c) sacrificial anodes.



Key Technical Point: Section 6, 6.2, 6.2.3 – CP of Underground Storage Tanks, Cathodic Protection, CP of Existing UST Systems

Because of the common grounding effect, the current required to cathodically protect the UST system is significantly greater than that required to protect an isolated system. As such, impressed current systems are typically required for cathodic protection of existing UST systems.



Key Technical Point: Section 7, 7.1 – CP of Above Ground Storage Tanks, Cathodic Protection

Depending on the temperature of the product, a design current density of 1 mA/ft^2 (10 mA/m^2) is usually sufficient to achieve NACE criteria for cathodic protection.



Key Technical Point: Section 7, 7.2 – CP of Above Ground Storage Tanks, Existing Tanks

Several different types of impressed current anode installations have been used to distribute the protective current to the tank bottom. However, when the design of the tank uses a containment liner that shields the CP current from the tank bottom (i.e. polyethylene liner), these methods of anode installation cannot be used.



Key Technical Point: Section 8, 8.2 – CP of Met Tower Guy Anchors, Cathodic Protection

In order for the galvanic anode system to provide effective protection to the guy anchors and meet the desired service life, it is important to take into account the additional surface area of buried structures that are electrically bonded to the tower.

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