Stray Current Localization and Mitigation for Effective Cathodic Protection of Pipe-Type Cable Systems

3002000881

Stray Current Localization and Mitigation for Effective Cathodic Protection of Pipe-Type Cable Systems

3002000881

Technical Update, December 2013

EPRI Project Manager

N. Murray

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATION PREPARED THIS REPORT:

Electric Power Research Institute (EPRI)

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2013 Electric Power Research Institute, Inc. All rights reserved.

ACKNOWLEDGMENTS

The following organization prepared this report:

Electric Power Research Institute (EPRI)
1300 West W.T. Harris Boulevard
Charlotte, NC 28262

Principal Investigator
N. Murray

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Stray Current Localization and Mitigation for Effective Cathodic Protection of Pipe-Type Cable Systems: State of the Art Report. EPRI, Palo Alto, CA: 2013. 3002000881.

PRODUCT DESCRIPTION

This report describes the initial stages of a project on detecting, monitoring, and mitigating the effects of stray current corrosion in pipe-type cable systems through the use of electrochemistry and pipeline transmission maintenance practices.

Background

Stray current corrosion can be attributed to either direct or alternating current sources and can result from a static or dynamic event. As a result, although stray current corrosion can be manageable in rural settings, it can be quite difficult to identify, diagnose and mitigate in congested urban environments because of the limited number of events.

Objectives

The goal of this project is to develop new tools or techniques to detect stray current corrosion in pipe-type cable systems, novel methods to mitigate or arrest the corrosion, and implementation of design changes to enhance these methods.

Approach

The project team identified gaps in existing maintenance programs for pipe-type cable systems through a state-of-the-art study and surveys of utility practices. The research approach is to apply the latest advances in cathodic protection systems and integrate them into a best practice stray current mitigation method. This approach will include new sensor development to monitor and diagnose both dynamic and static stray current events and new controls for protection systems.

Results

Traditional pipeline techniques such as the close interval survey and side drain technique work well to identify the location of coating flaws and sources of stray currents when in a rural environment. Special considerations must be made when survey work is on concrete or asphalt in urban settings to provide access to the soil. Once the coating flaw locations are identified, the survey must determine the current requirements to mitigate any stray currents present or what method must be used to drain the current from the pipe casing and eliminate the damaging effects.

Applications, Value, and Use

The next phase of this project will identify new cathodic protection system developments and evaluate the efficacy of those technologies at EPRI's Underground Transmission Facilities.

Keywords

Cathodic disbondment
Corrosion
Pipe-type cable
Inspection
Stray current
Cathodic protection
Mitigation

ABSTRACT

Stray current corrosion in pipe-type cable systems can result from many sources within a right of way. The effects can be quite serious and result in outages, property damage or fatalities. Fortunately, many of the techniques used in pipeline transmission will transfer to pipe-type cable systems such as inspection and assessment, coating applications, and mitigation methods.

This report outlines state-of-the-art techniques and technologies that may be used in the design, construction, and maintenance of pipe-type cable systems to prevent and manage stray current corrosion. This report also identifies gaps in each area for future research.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
BACKGROUND

Stray current corrosion occurs on a variety of transmission structures and can lead to catastrophic failures if not properly diagnosed, located, and mitigated. Often the diagnosis requires extensive planning and mitigation methods designed for a specific application.

Some factors that influence the severity of ac corrosion are:

- Tangent points where an overhead transmission line crosses or moves away from the underground pipe-type cable
- Localized, low soil resistivity
- Areas of changing moisture or aeration
- Size of the holiday or coating system flaw
- Condition of the pipeline coating

The History of Stray Current Corrosion

Sir Humphrey Davy first reported an observation of external current-induced corrosion in 1812 in laboratory experiments with iron in an acid exposure test with high corrosion rates. Davy established that there is a proportion between the mass of metal reacted and the current applied.

In 1887, it was reported in Brooklyn, New York that iron pipes were affected by the presence of stray currents originating from rail line operations. Similar observations followed in 1893 in Great Britain, in 1904 in Germany, and then again in 1916 in Melbourne, Australia. In 1910, the first guidelines were published for limiting stray direct currents in order to protect gas and water pipelines.

Test Facilities in Charlotte

The Charlotte underground transmission test facilities were used to validate the inspection methods outlined in the following chapters, but the disbondment testing was completed in the Charlotte corrosion laboratories

2

CORROSION TYPES AND CAUSES

There are many factors that govern or influence the initiation and sustainability of a corrosion cell. These factors can range from environmental factors, design flaws, and operations errors to excessive time intervals for maintenance cycles. This chapter outlines types of corrosion within the power generation and delivery sectors with an emphasis on corrosion types specific to pipe-type cable systems. The following corrosion types will be discussed within this chapter:

- General corrosion (uniform)
- Pitting (localized)
- Galvanic
- Concentration cell (differential oxygen or moisture)
- Metal ion cell
- Fatigue
- Microbial
- Long-line effects
- Stray current (AC or DC)

General Corrosion

General corrosion is not typically found on buried pipe-type cable systems but can be found in more acidic soils. Localized corrosion is then typically found in near-neutral soils and inititates due to anomalies within the microstructure or surface defects of the pipe. Localized corrosion will typically collapse into general corrosion due to the soil type and lack of driving potentials (see Figure 2-1) .

The acidity or alkalinity of the environment is an important factor in corrosion. The hydrogen ion concentration of the soil or water in which a structure is located can affect the corrosiveness of the environment and the current required for cathodic protection. The hydrogen ion concentration is expressed in terms of pH. Stated mathematically, the pH value is the logarithm of the reciprocal of the hydrogen ion concentration. A change of one in pH value is equivalent to a change of ten times in concentration. pH values range from 0 to 14 with 0 to 7 being acidic, 7 being neutral, and 7 to 14 being alkaline.

Figure 2-1
Well drained soils are typically neutral in pH and do not support localized corrosion

pH readings may be taken with a meter in the field or on a separate soil sample. Most soils are slightly acidic and range from about 5.5 to about 6.5 in pH. More acidic soils, particularly those with a pH below 4, are highly conducive to corrosion activity. While localized pitting occurs quite often within soils that are relatively neutral, acidic soils will support more widespread or generalized corrosion.

Chemical corrosion is damage that can be attributed entirely to chemical attack without the additional effect of electron transfer. This type of corrosion often affects amphoteric materials such as zinc, tin, lead, aluminum, and beryllium that are sensitive to exposure to either extremely acidic or alkaline solutions. Aluminum, for example, corrodes under both low and high pH conditions as shown in Figure 2-2. Amphoteric metals should only be used within a limited pH range due their sensitivity to chemical corrosion.

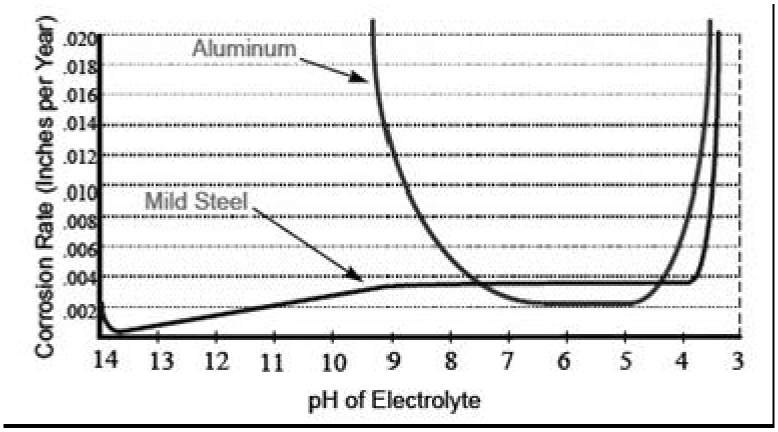


Figure 2-2
Effects of pH on ferrous metal vs. an amphoteric metal

Examples of corrosive solutions that can promote chemical corrosion include incompletely cured concrete, acetic acid from volatilized wood or jute, waste products from industrial plants, and water with a large amount of dissolved oxygen. Other compounds known to increase copper dissolution include pesticides, herbicides, fertilizers, and airborne pollution.

Pitting Corrosion

Pitting corrosion typically initiates at a small anomaly in the microstructure or surface irregularity and can have a high corrosion rate within a small area the results in a high penetration rate. The morphology of a corrosion pit is such that the root of the pit is the cathodic regime and the surrounding rim or edge of the pit is the anodic regime. Ionic migration occurs within the root of the pit if the cathode-to-anode area is sufficiently large to support that high penetration rate.

Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals are connected in an electrolyte and have sufficient potential differences to result in a high driving potential. Good examples of this type of corrosion are galvanized carbon steel transmission structures that are connected to copper grounding systems. In low resistivity soils the galvanizing has a short service life, and the structure substrate is exposed to the soil.

Concentration Cell

Concentration-cell corrosion results from differences within the structure environment such as temperature, moisture or oxygen content, and differences in the oxidation states. A good example of concentration-cell corrosion is concrete encased steel where the steel potential outside the concrete is significantly more electronegative than the steel within the concrete. This driving potential resulting in a thin band of corrosion located where the steel protrudes from the concrete foundation (see Figure 2-3).

Figure 2-3
Concentration cell corrosion on a stub angle configuration

Another example of concentration-cell corrosion is structures placed within a tidal zone in a marine environment. Figure 2-4 illustrates an H pile installed in a well-aerated environment with 200,000-ppm oxygen content while the mudline was in an anaerobic environment with 7-ppm oxygen. The difference in aeration levels results in a significant driving potential and corrosion rates that consumes three-quarters of the steel within a 20-year period.

Figure 2-4
Steel H Pile installed in a marine environment

Weathering steel is an alloy specifically designed to form a dense, well adhered corrosion product when exposed to a specific range of environmental factors. The thresholds for these factors are not well defined (additional research is required), but time of wetness (TOW) and specific ionic species govern the oxide-type formation in these steels (see Figure 2-5).

Incompatible environments result in an immature oxide formation with a grainy, porous texture with poor adhesion to the substrate. This porous texture holds precipitation and condensation quite often containing contaminants in solution. Retained moisture extends the TOW and allows corrosion to form additional layers of loose oxides while creating mechanical stresses within bolting details. These stresses often exceed the material strength of the structural members and fasteners causing deformation and formation of a gap between mating surfaces (see Figure 2-6).

The mural tri force diagram illustrates the specific environmental factors that govern the evolution of the three primary oxide formations into goethite. Goethite is the final oxide formation and is tightly adhered, amorphous, and considered a protective patina.

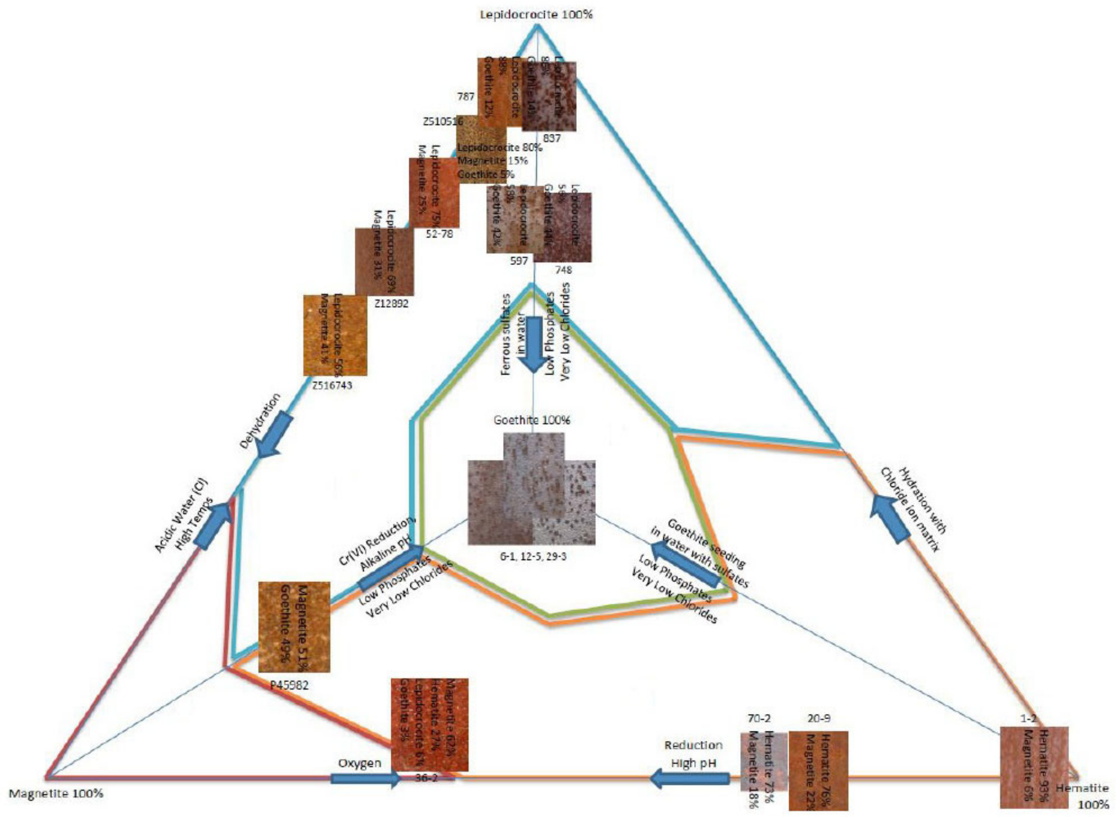


Figure 2-5
Mural Tri Force diagram illustrating the four primary oxide formations and governing environmental factors

Figure 2-6
Illustration of weathering steel packout and stresses within a bolt detail

Structural failure due to fatigue is not common in the design of transmission structures because most materials are not high strength steel and the design allows flexure. Pipelines and tubular structures, however, may suffer from hydrogen embrittlement due to electrolysis of soil moisture when over-polarized by cathodic protection. The combination of operating temperatures and cathodic protection create thermal and electrical stresses. Some coating systems have insufficient adhesion, which results in a disbonded coating system exposing additional surface area, lowering the current density and increasing the probability of a corrosion cell formation.

Figure 2-7
Illustration of fatigue damage on a transmission tower leg

Microbiological induced corrosion (MIC) can occur due an exposure to either the environment or the metabolism of bacteria. Sulfate-reducing bacteria (SRB) will metabolize sulfates in the soil and deposit them on the surface of the structure while some bacteria will metabolize the steel directly (Figure 2-8).

Figure 2-8
Sulfate-reducing bacteria colonizing a tower leg with tubercles

Internal corrosion may occur within a pipe when there is turbulent flow and/or electrolysis resulting in the formation of gas pockets. Oil analysis may identify the presence of oxide formations, but disassociated gases are typically measured through sampling and analytical chemistry.

Figure 2-9
Internal corrosion damage on a pipe

Stray Current Corrosion

Stray current corrosion can be attributed to both alternating and direct current sources. The source governs not only the waveform and morphology of the corrosion damage, but also the location of the corrosion cell and the severity. The most common method of identifying the presence of stray currents is through pipe-to-soil potentials (see Figure 2-10).

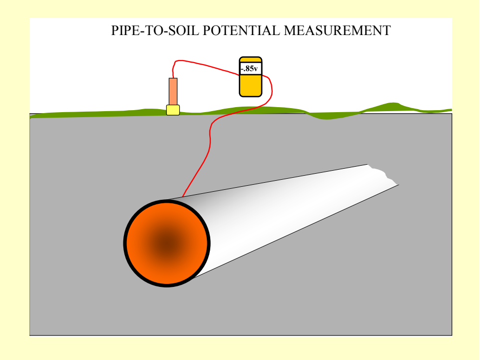


Figure 2-10
Pipe-to-soil potential measurements to identify the presence of stray currents

DC Corrosion Sources

There are many sources of dc corrosion which include long-line effects, dc traction engines, cathodic protection systems, welding operations, high-voltage transmission lines, and industrial smelting operations and telecommunications systems (see Figure 2-11, Figure 2-12, Figure 2-13, and Figure 2-14).

Figure 2-11
Direct current stray current corrosion (long-line effects)

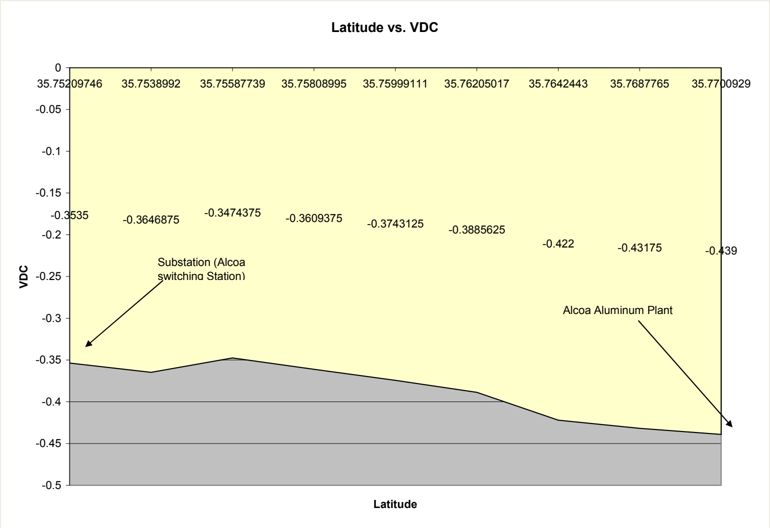


Figure 2-12
Survey identification of the dc stray-current source through a close interval survey

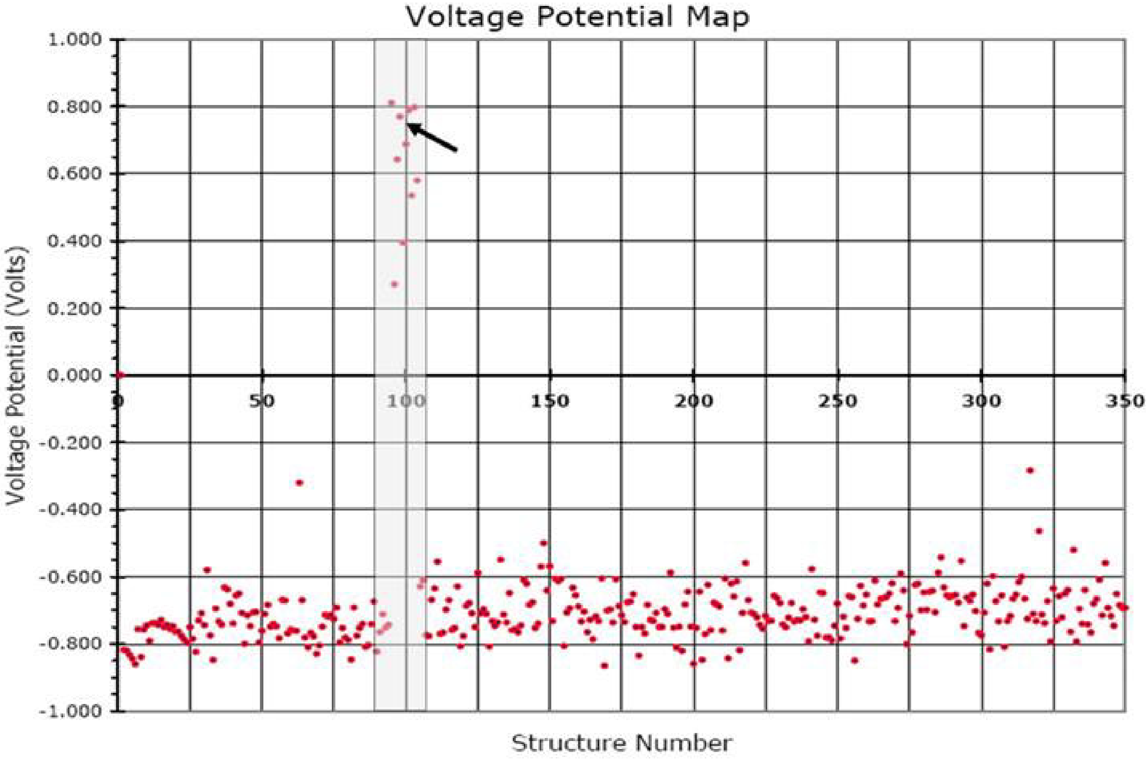


Figure 2-13
Stray-current corrosion from HVDC insulator leakage

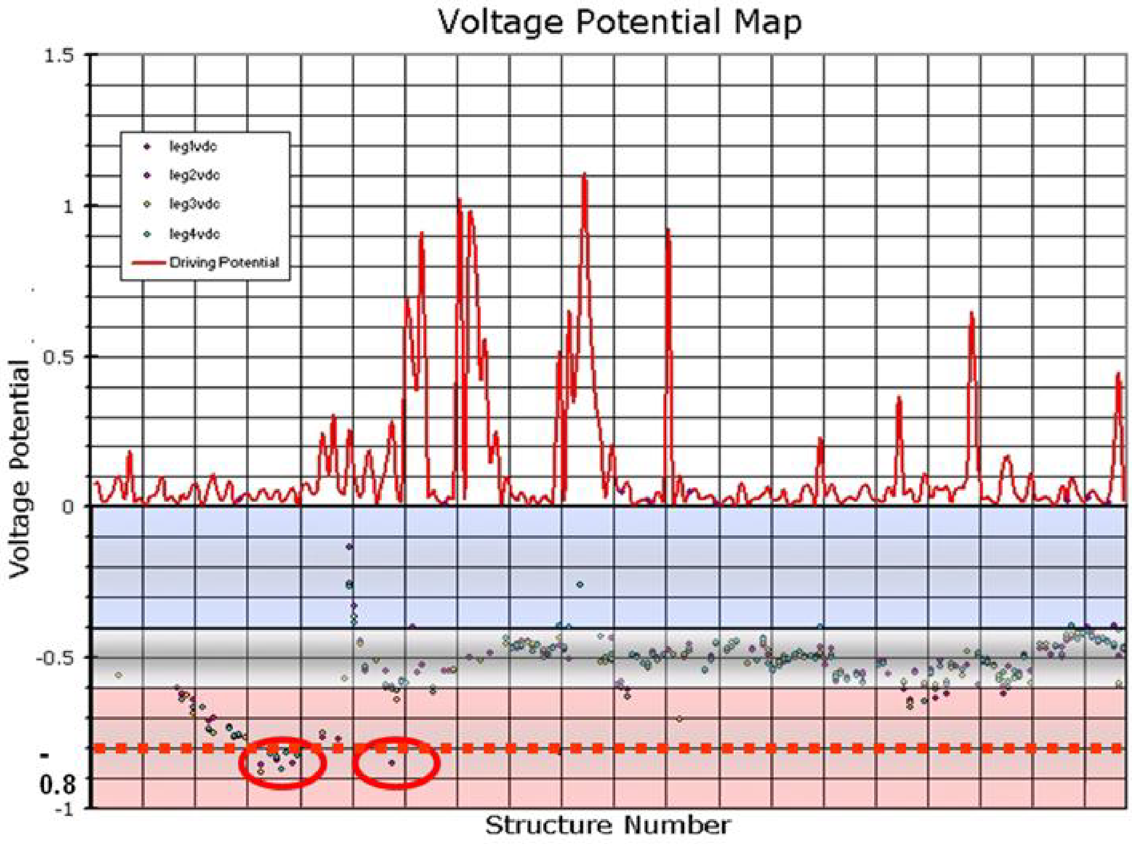


Figure 2-14
DC stray-current corrosion from a natural gas pipeline cathodic protection system

AC Corrosion Sources

There is a long list of ac corrosion sources, which include overhead transmission lines, ac traction engines, telluric (geomagnetic) effects, insulator leakage, and unbalanced transformer loads (see Figure 2-15, Figure 2-16, and Figure 2-17.

AC corrosion morphology is characterized by:

- Round hemispherical shape
- Specific colors
- Smooth edges
- Pimpled Pattern
- Brown discoloration
- Corrosion product is not soluble
- PH neutral to elevated

There are also some guidelines for AC corrosion thresholds for current density requirements. They are as follows:

- AC corrosion does not occur < 20 A/m^2
- AC-corrosion is unpredictable 20 to 100 A/m^2
- AC corrosion occurs >100 A/m^2

Figure 2-15
Illustration of ac corrosion damage on a pipeline

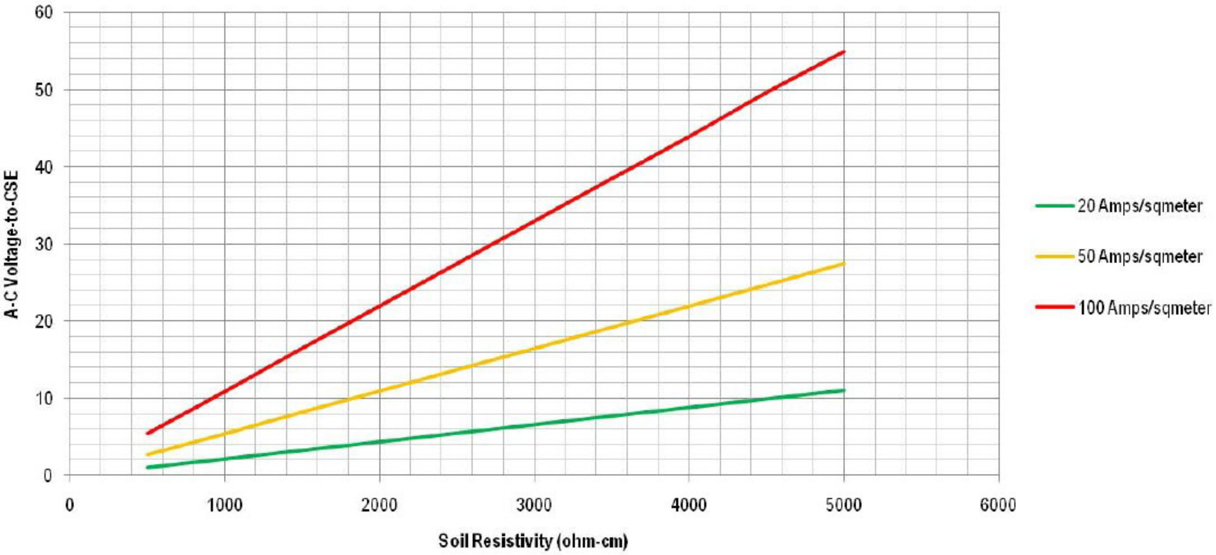


Figure 2-16
AC potentials as a function of soil resistivity

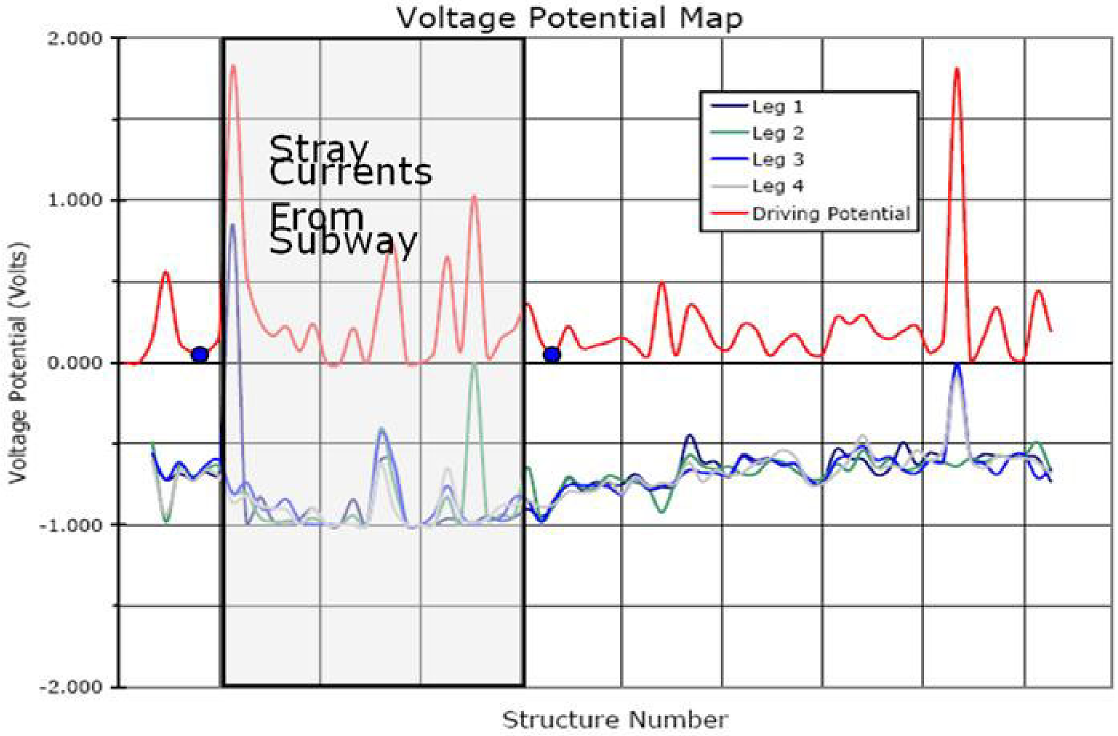


Figure 2-17
AC stray current corrosion from a railroad

3

CHEMISTRY, MODELING, AND LABORATORY TEST METHODS

The consumption rate of carbon steel is 20 pounds of steel lost for each ampere of direct current leaving a structure in one year. The following is the derivation of that consumption rate where iron (Fe) has an atomic number of 26, 26 protons and 30 neutrons, and a molar mass of 55.845 grams per mole (6.022 x 10^{23} atoms). The most common ions of iron are ferrous (Fe^{+2}) and ferric (Fe^{+3}). Water in the soil disassociates into hydrogen ions (H^{+}) and hydroxyl ions (OH^{-}). The following reactions are found in a typical corrosion cell:

$Fe(s) \Rightarrow Fe^{+2}(aq) + 2e^{-}$

$2H+ (aq) + 2e^{-} \Rightarrow H_2(g)$

$Fe^{+2}(aq) + 2OH^{-} \Rightarrow Fe(OH)_2$

The equivalent weight may be defined as the mass of a substance that will react with one mole of electrons in an oxidation – reduction (REDOX) reaction. The first ionization state of iron from Fe to Fe^{+2} has a molar mass (M) of 55.845 grams per mole and the number of moles (z) of electrons transferred in the reaction is 2.

$M/z = 55.845/2 = 27.923g$ **Equation 1 Equivalent Weight Calculation**

Using Faraday's law:

$m = (Q/F)(M/z)$ **Equation 2 Faraday's Law**

Where:

m = the mass liberated in grams (g)

Q = the total charge transferred in the reaction in coulombs (C)

F = Faraday constant 96,485 coulombs per mole of electrons ($C\text{-}mol^{-1}$)

M = the molar mass of the substance in grams per mole ($g\text{-}mol^{-1}$)

z = the number of moles of electrons transferred per number of moles of substance

To calculate the mass of iron altered due to the flow of one (1) ampere of stray current for a year, recall that the ampere is equivalent to the flow of one (1) coulomb of charge per second.

$I = Q/t = 1C/ 1s = 1A$

There are 31,536,000 seconds in one year; therefore, the charge transfer in one year is equal to:

$Q = It = (1\ C/s)(31{,}536{,}000s) = 31{,}536{,}000C$

The number of moles of electrons transferred in the reaction is then:

$Q/F = 31{,}536{,}000/\ 96{,}485 = 327$ moles

Where:

$m = (Q/F)\ (M/z) = (327)(27.923) = 9{,}131g$

W = 9.131kg* 2.2 lb/kg = 20lbs lost per year at one (1) ampere of DC current

Alternating Current Corrosion

While most corrosion reactions may have a driving potential of hundreds of millivolts, stray-current corrosion may have driving potentials of tens of volts. Therefore, stray-current corrosion reactions can be typically 100 to 1,000 times faster than other forms of corrosion.

See iAC = $8V_{AC}/\sigma\Pi d$Equation 3. When calculating alternating current density at a coating holiday on a pipeline.

$$\mathbf{i_{AC} = 8V_{AC}/\sigma\Pi d}$$ **Equation 3 Alternating Current Density**

Where:

i_{AC} = alternating current density (amperes/meter^2)

d = diameter of holiday (meters)

V_{AC} = ac voltage of the pipeline

s = soil resistivity (ohm-meter)

Structure to Soil Potential Model

Direct corrosion models on a pipe-type cable system are defined by three primary reactions, which occur at the anodic or cathodic sites. The oxidation reaction is the liberation of two electrons with oxide formation while the reduction reaction consumes those electrons and generates hydroxyl ions and electrolysis disassociates water into hydrogen and hydroxyl ions.

Fe → Fe2+ + 2e– **Equation 4 Corrosion of Steel**

O2 + 2H2O + 4e– → 4OH– **Equation 5 Reduction of Oxygen**

H2O + 2e– → H2 + 2OH– **Equation 6 Hydrogen Evolution**

$$i = 10^{\frac{\Phi - E_{Fe}}{\beta_{Fe}}} - \left(\frac{1}{i_{lim,O_2}} + 10^{\frac{\Phi - E_{O_2}}{\beta_{O_2}}} \right)^{-1} - 10^{\frac{-(\Phi - E_{H_2})}{\beta_{H_2}}}$$

Equation 7 Polarization Curve for the Contributions of the Three Reactions

Where:

$I_{lim,O2}$ = net current density

E_{Fe} = equilibrium potential of iron

β_{Fe} = Tafel slope of iron dissolution

E_{O2} = equilibrium potential of oxygen

β_{O2} = Tafel slope of oxygen reduction

E_{H2} = equilibrium potential of hydrogen

β_{H2} = Tafel slope of hydrogen evolution

The mass-transfer-limited current density for reduction of oxygen has a critical influence on the corrosion potential for steel with a bright new finish while the presence of scale deposits are characterized by a smaller mass-transfer-limited current density for oxygen reduction. Variations caused by differences in moisture content or soil composition will influence the coupon off-potential. This type of corrosion is called concentration cell corrosion and occurs regularly on pipelines and pipe-type cable systems.

Research has shown that the initiation mechanism for the Pritec-coating failure mode is a combination of thermal and mechanical stresses. Epoxy-repair-coating failure initiation mechanisms are thermal and electrical stresses but could include mechanical stresses and can be understood using this model.

$$i = 10^{\frac{\Phi - E_{Fe}}{\beta_{Fe}}} - \left(\frac{1}{i_{lim,O_2}} + 10^{\frac{\Phi - E_{O_2}}{\beta_{O_2}}} \right)^{-1} - 10^{\frac{-(\Phi - E_{H_2})}{\beta_{H_2}}}$$

Equation 7 (includes coating system parameters for moisture uptake in the model which are found in Table 3-1)

Table 3-1
Polarization curve parameters used in the model

Parameter	Value	Units
$I_{\text{lim,O2}}$	0.1,1.0,3.16,10.0	$\mu A/cm^2$
E_{Fe}	-526	mV_{cse}
β_{Fe}	59	mV/decade
E_{O2}	-104	mV_{cse}
β_{O2}	59	mV/decade
E_{H2}	-955	mV_{cse}
β_{H2}	118	mV/decade

Measuring water uptake by the coating systems provides parameters for a case study and an expression for the off-potential underneath the coating. Equation 8 accounts for coating permeability and the small amount of current that passes through.

$$\frac{A(\Phi - \Phi_{\text{in}})}{A_{\text{pore}}\rho_{\text{film}}\delta_{\text{film}}} = 10^{\frac{\Phi_{\text{in}} - E_{Fe}}{\beta_{Fe}}} - \left[\frac{1}{(1-\alpha_{\text{block}})i_{\text{lim},O_2}} + 10^{\frac{\Phi_{\text{in}} - E_{O_2}}{\beta_{O_2}}}\right]^{-1} - 10^{\frac{-(\Phi_{\text{in}} - E_{H_2})}{\beta_{H_2}}}$$

Equation 8 Expression for off-potential calculations in the model

Coating parameters used in the model are included in Table 3-2 and are needed to define pre and post aging performance.

Table 3-2
Coating parameters

Parameter	Values	Units
A/A_{pore}	1000	-
ρ	5×10^9	Ω-cm
δ	20	Mils
α_{block}	0.99	% Effective

A/A_{pore} = ratio of surface area to pore area

ρ = resistivity of the coating

δ = coating thickness

α_{block} = fractional reduction of the transport of oxygen

ϕ = off-potential under the coating

The benefit of forecasting off-potentials is that it provides an understanding of the substrate condition within the coating system pore. Forecasts may be validated through electrochemical impedance spectroscopy (EIS) and monitoring impedance change

Electrochemical Impedance Spectroscopy (EIS) Measurements

To evaluate coating systems in terms of their corrosion resistance and potential to degrade when exposed to corrosive test solutions, testing follows ASTM G106 - 89(2004) Standard Practice for Verification of Algorithm and Equipment for Electrochemical Impedance Measurements[4]. This standard practice provides a method to verify instrumentation and techniques for collecting and presenting electrochemical impedance data. Using this method, subtle coating changes can be detected and measured by monitoring the electrochemical behavior of a coating system.

EIS Overview

Initial EIS measurements are obtained on coated panels prior to accelerated exposure testing to provide a base-line measurement. After the exposure period is complete, EIS measurements are again taken and then compared to the initial EIS measurements. The following coating properties can be determined by EIS:

- Capacitance
- Pore resistance
- Moisture absorption

When a coating is exposed to a test solution, a decrease in electrochemical impedance will be seen as a function of time. The decrease shows the breakdown and permeation of a coating by the test solution.

EIS evaluation exploits the changing frequency-dependent impedance of coatings during exposure testing to assess the degradation, permeability, and water absorption of coatings. Non-conductive coatings that have not failed will exhibit dominant insulative capacitive impedance. When coatings become permeated, penetrated, or absorb enough moisture to bridge from the exterior to the substrate metal, the resistance at low frequencies drops. Resistance becomes bounded at the high end by the “pore resistance” or the equivalent electrical resistance in parallel with the capacitance of the coating.

Good coatings have high impedance—impedance is the ratio of the applied voltage to the current flowing and varies with the frequency of the applied voltage. Good coatings with high impedance allow very little current flow at low frequencies, which is critical because current flow is a key process in corrosion.

Impedance considers:

- The dependence of an applied voltage signal on the frequency
- The phase shift between a sinusoidal applied voltage signal and the resulting current signal

Thus, both the “magnitude” and the “phase” are parts of the concept of impedance.

Traditional Test Setup

The test setup applies a sinusoidal voltage across the coating and measures the resulting currents. Both the ratio of voltage to current and the phase shift of the voltage are measured. A conductive metal substrate is used to make electrical contact to one side of the coating. To make contact with the other side, a glass vessel is sealed to the coating and filled with an electrolyte, i.e., a liquid capable of carrying current (see Figure 3-1).

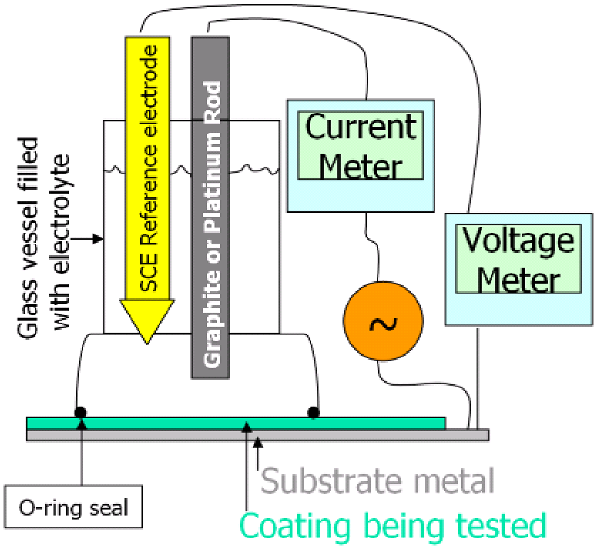


Figure 3-1
Test setup for EIS testing

A computerized electrochemical system and EIS software are used to assist with data collection and analysis. A computer controls the voltage across the coating by injecting current through the platinum or graphite electrode in the electrolyte. The current and voltage are monitored continuously. Analysis of the resulting data yields the magnitude of the impedance and the phase between current and voltage. Measurement examples of EIS before and after hot acidic immersion exposure testing are shown in Table 3-3.

Table 3-3
Example of EIS measurements before and after hot acidic immersion exposure testing

Test ID	Time exposure to hot acidic chloride immersion (hours)	Percentage of initial protection	Capacitance (pF)	Pore resistance (Rp, 10^9ohm)	Water uptakes (vol. %)
Coating System A	0	100%	270	144.5	0
	336	95%	290	0.006262	1.6
Coating System B	0	100%	256	0.8	0
	336	94%	373	0.004013	9.1

4

INSPECTION AND ASSESSMENT

Identifying the Presence of Stray Currents

The underground test facilities in Charlotte were instrumental in the research contained within this chapter and the next. The facilities contain test samples that are installed in various backfills with specific coating flaws so that location and clocking of the holidays are known (see Figure 4-1). The facility has two rectifiers, one that protects the main test pipe segments and the other that protects the irrigation supply crossing. The setup represents stray current interference on the test pipe segments and can be monitored through the terminal stations that monitor potentials, temperature, and moisture levels on each pipe segment. The data stream to a radio frequency (RF) modem and is uploaded to a website for analysis. Each terminal station contains coupons, one of which is connected to the pipeline and shares protection from the rectifier while the other freely corrodes in the backfill. These data are currently manually uploaded but will become streaming in the near future.

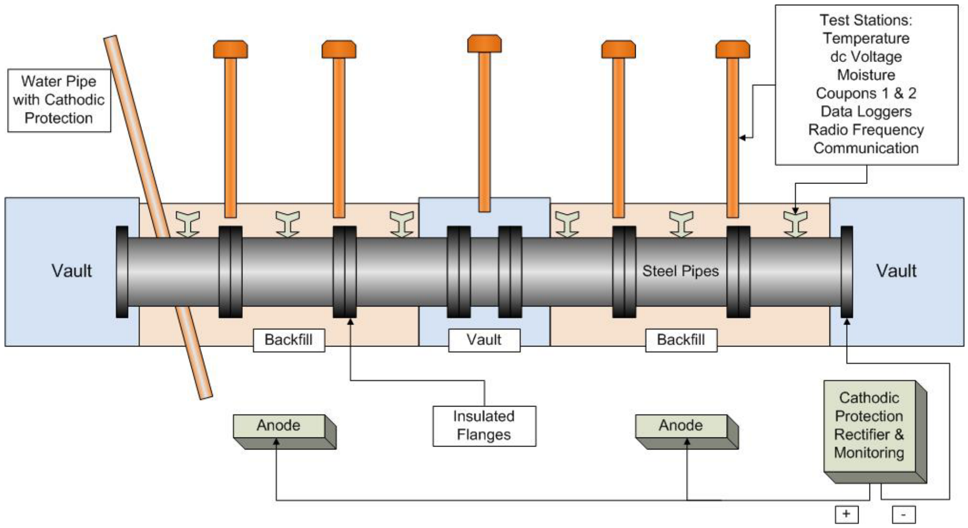


Figure 4-1
Charlotte Underground Test Facility layout

Identification of possible stray currents may be completed through the use of a close interval survey (CIS). A CIS is usually used to determine cathodic protection levels, electrical contact with other structures, areas of current shielding, and large coating holidays. In CIS measurements, the profile of potential (IR) between the steel pipe and an electrode above the pipe along the entire route is recorded. CIS can identify possible interference areas and shorted casings.

In this test, a current interrupter was applied to the test pipe sections. On-off periods (2 seconds on and 8 seconds off) were set for the interval. Potential measurements were made at regular intervals of approximately 3 to 5 ft apart using a high impedance voltmeter and a Cu-CuSO4 reference cell. A calibration of the reference cell was made before the survey began. The test procedure included:

- Connecting the current interrupter to the test pipe sections
- Connecting the positive lead of the voltmeter to the terminal station
- Connecting the reference cell to the negative lead of the voltmeter
- Collecting a potential measurement at regular intervals and recording on and instant off potentials
- Graphing on and instant off potentials in distance domain

Results of the CIS are shown in Figure 4-2. In this survey, the CP system for the feed-line pipe was turned on; and the CP system for the test pipe sections was off. The power supply with current interrupter was connected to the test pipe sections. The measurements started from Pipe # 1 through the length of the installation.

The plots in Figure 4-2 show that the test pipe was sufficiently polarized along its length. Potential drops were observed at 4 locations. The first location was at about 13 ft (4 m) from the vault end of Pipe # 1. This location was about 4 ft (1.2 m) away from a flaw (7/8 inch diameter, 0.08 inch depth, 9 o'clock) on pipe # 1. This pipe section was backfilled by native soil. The second location was at about 43 ft (13 m) from the vault end of Pipe # 1. At this location, Pipes # 2 and 3 were connected through an insulating flange. This location is also where Terminal Station #2 with test coupons was located. The third and fourth locations were at about 75 to 79 ft (23 to 24 m) near the flaw (7/8 inch diameter, 0.16 inch depth, 12 o'clock) on Pipe # 5. This section of pipe was backfilled by gravel. It appeared that the CIS was effective in detecting flaws of significant sizes (e.g., 7/8 inch diameter) in native soil and gravel backfills.

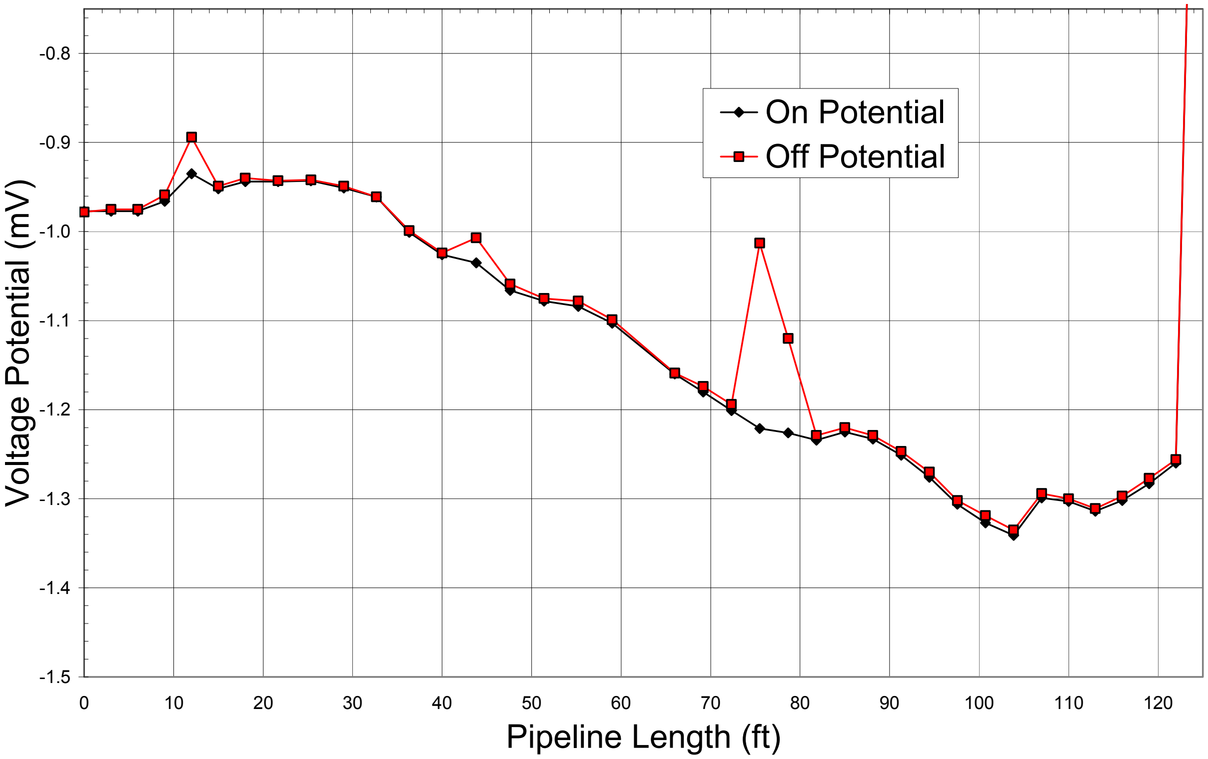


Figure 4-2
Close interval survey using auxiliary power supply and interrupter connected to test pipe sections – CP system for feed line pipe was off, distance starting from the vault end of Pipe #1

Locating Stray Currents

The side drain survey measures potential drops or differential potentials between two reference cells. This survey is a directionally sensitive technique and is often used to detect the source of stray currents in addition to the location of holidays. One reference cell was positioned over the pipe while the other was offset to the side of the pipe sections for 5 to 10 ft (1.5 to 3.0 m). An initial calibration of the reference cell was performed. The survey was completed on both sides of the pipe installation. The test procedure included:

- Connecting a reference cell to the positive lead of a voltmeter
- Connecting another reference cell to the negative lead of a voltmeter
- Placing the reference cell connected to the positive lead of the voltmeter over the pipe sections and the other off to the side
- Collecting a differential potential measurement at each 3 to 5 ft (0.9 to 1.5 m) interval
- Flagging the areas that show an increased or decreased potential difference—negative polarity shows current flow off the pipe installation while positive polarity shows current flowing on the pipe installation.
- Graphing the differential potential measurements as a function of distance

Results of the side drain survey are shown in Figure 4-3, Figure 4-4, Figure 4-5, and Figure 4-6. The measurements started from Pipe # 1 through the length of the pipe installation. Figure 4-3 shows the plots when both the CP systems were on as a baseline.

Figure 4-4 shows the plots when only the CP system for the feed line pipe was on. The results show that the first sweep and the return sweep created crossings near the holiday locations. Table 4-1 summarizes the results of the crossing locations compared with the holiday locations. The results indicated that this aboveground survey could identify locations of the holidays created on the pipe sections with reasonable accuracy (error of less than 6 ft (1.8 m) for this case) if backfills of native soil and gravel were used. The survey was effective for both coating types (Pritec and fusion-bonded epoxy) used in this case and for all sizes of flaws. In the section where mixed cement and sand backfill was used, this survey did not provide clear indication for the flaws on Pipes # 6 and 7. This failure is very likely because of the high electrical resistivity of this type of backfill and the alkaline environment it created.

Table 4-1
Holiday locations compared to crossing locations in side drain survey

Holiday (#)	Holiday Location (ft)	Crossing Locations (ft)	Difference (ft)
1	9	13	4
2	31	30	1
3	52	46	6
3	52	51	1
4	77	75	2
5	98	(84) estimated	-
6	120	(110) estimated	-

Figure 4-5 shows the plots when just the test pipe CP system was on. Figure 4-6 shows the results when both CP systems were off. In this last case, the potentials measured were low and were likely created by stray currents from other localized sources. Subsequent testing with both rectifiers turned off revealed that the unknown stray current source was from high-temperature conductor testing in a laboratory more than 150 ft (46 m) from the underground corrosion test facility.

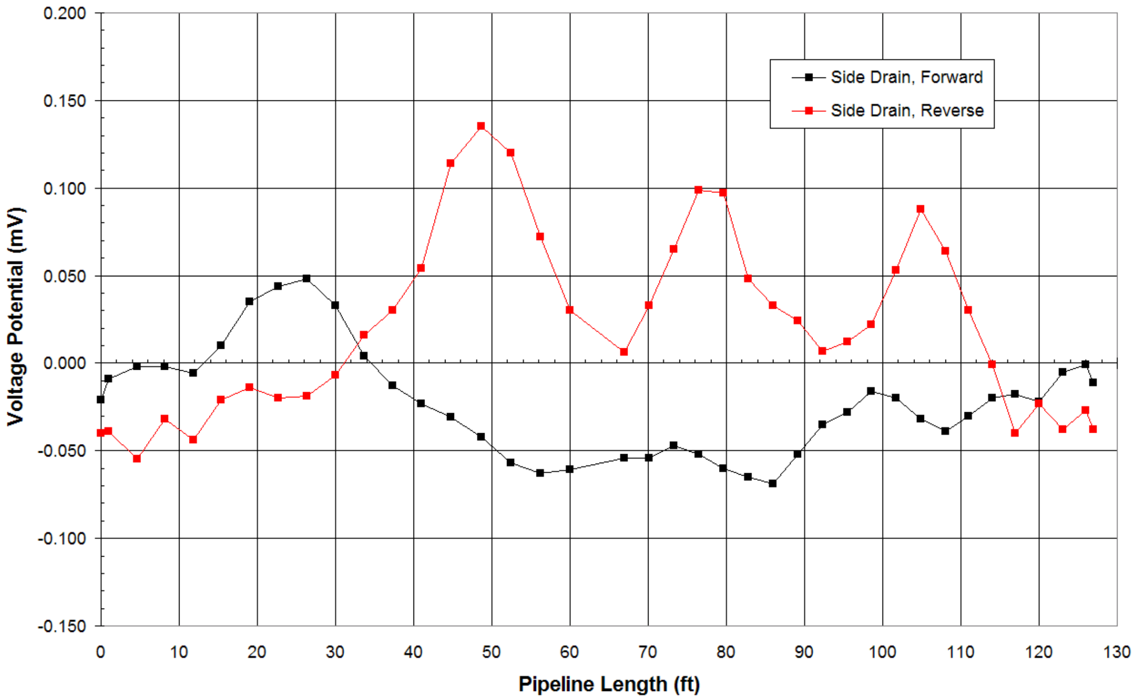


Figure 4-3
Side drain survey – Both CP systems were on, distance starting from the vault end of Pipe #1

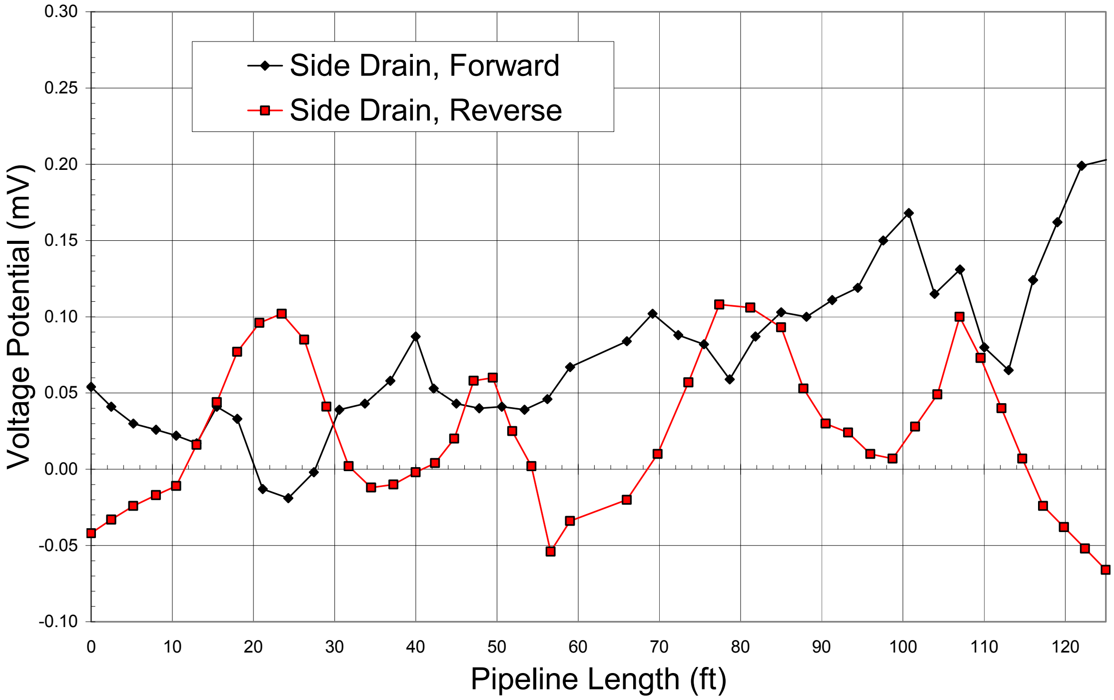


Figure 4-4
Side drain survey – CP system for feed line pipe was on, distance starting from the vault end of Pipe #1

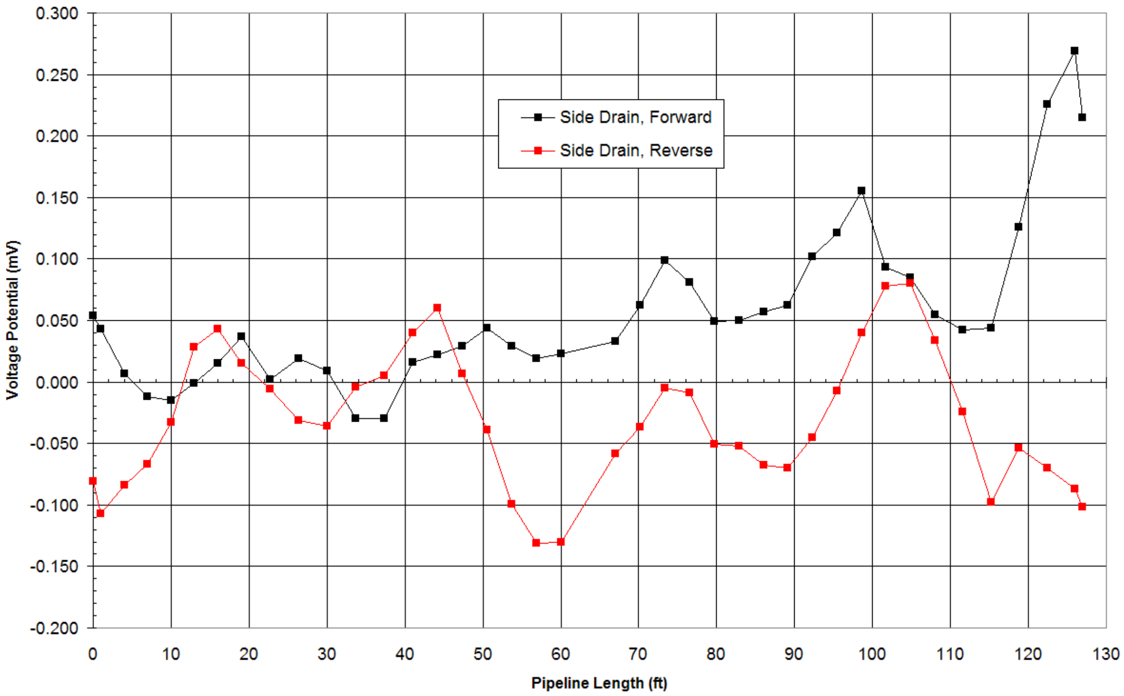


Figure 4-5
Side drain survey – Test Pipe CP system was on, distance starting from the vault end of Pipe #1

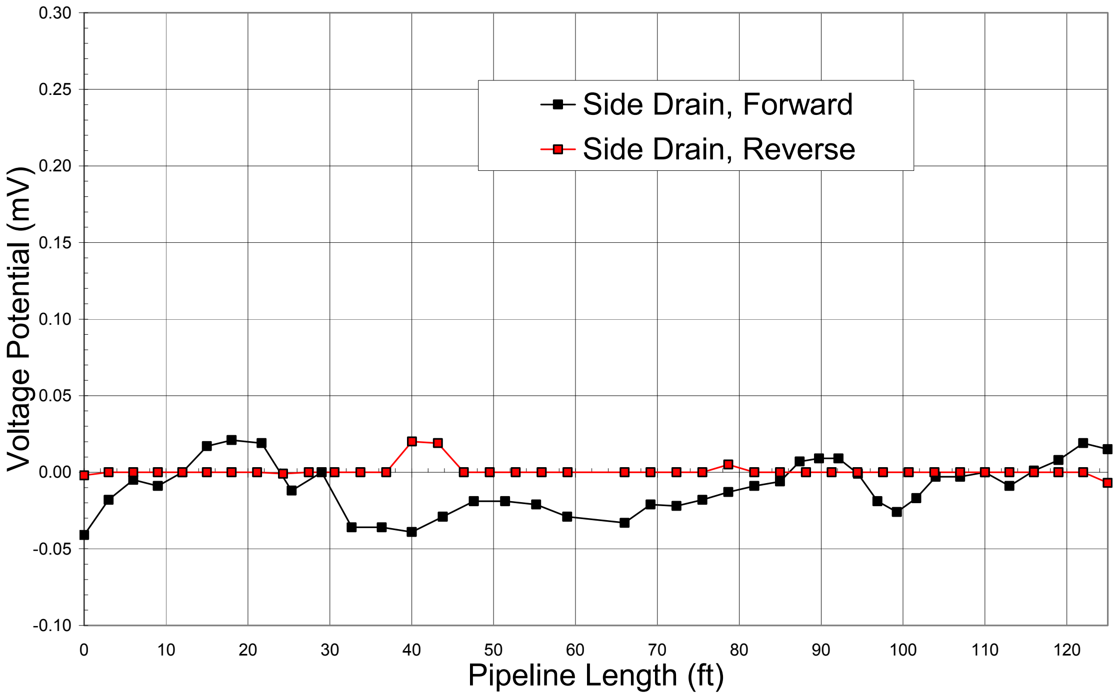


Figure 4-6
Side drain survey – Both CP systems were off, distance starting from the vault end of Pipe #1

Measurement of Stray Currents

Methods to measure stray currents have been studied, developed, and implemented within the pipeline industry throughout the last century. These techniques may be used to both quantify the magnitude of the stray current effects, but also to quantify the size of the holiday resulting in exposure to the environment.

Measuring Pipe Resistance

The traditional method used to measure resistance in a pipe section is to measure voltage drop through a calibrated span. To construct a calibrated span, a pipe length must have four insulated leads welded to the pipe at equidistant intervals for a voltage drop measurement (see Figure 4-7).

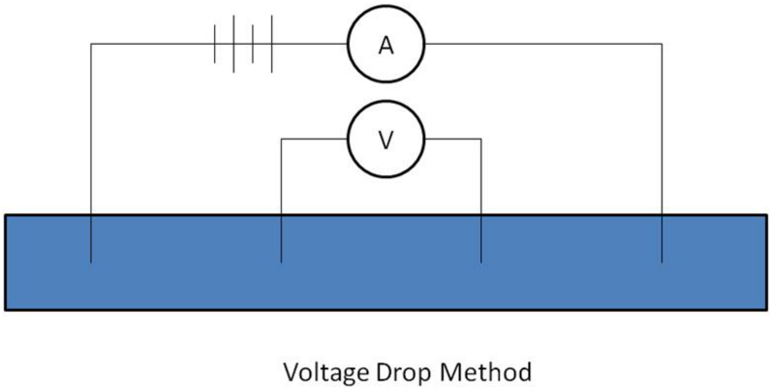


Figure 4-7
Calculating pipe resistance using a calibrated span to measure voltage drop

Stray Current Measurement

More elegant methods were developed that would reduce the voltage measurement to zero as the resistance was adjusted. This procedure would provide a current measurement and eliminate the need for equidistant spacing of the leads (see Figure 4-8).

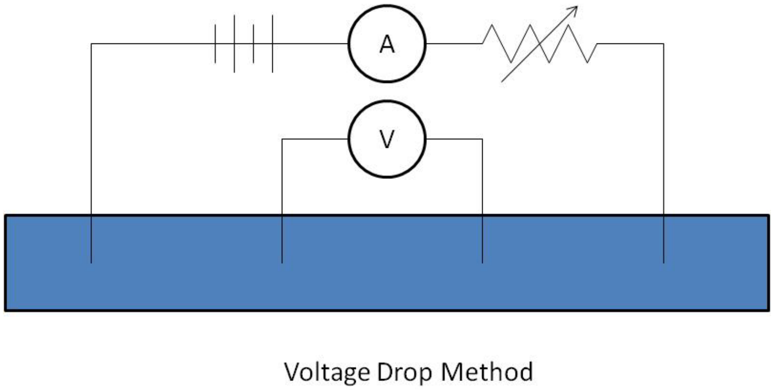


Figure 4-8
Calculating stray currents without a calibrated span

5

MITIGATION METHODS

Most pipeline methods commonly used to mitigate the effects of stray currents such as cathodic protection systems, coating system application, ac and dc mitigation, galvanic decouplers, and deep ground beds transfer to pipe-type cable installations. Stray currents may be a static condition or a dynamic event, and corrosion rates may be constant or intermittent. Dynamic events are more difficult to diagnose and require additional data collection equipment (see Figure 5-1).

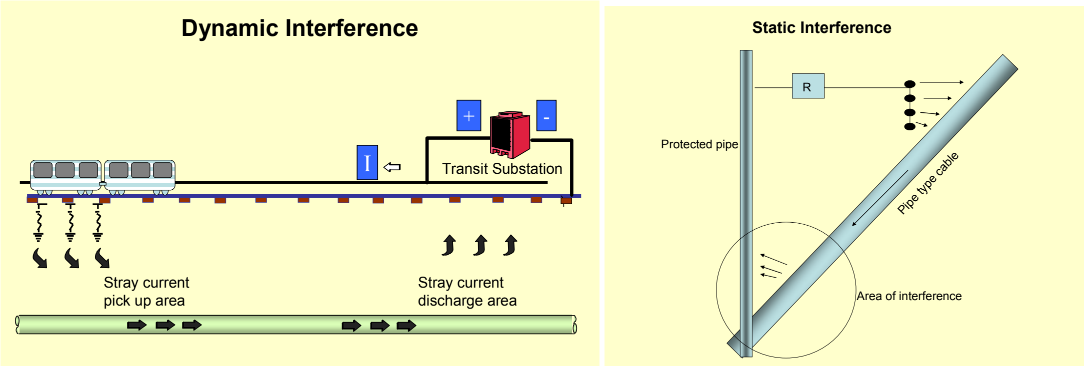


Figure 5-1
An example of dynamic stray current sources (left) and static stray current sources (right)

Alternating and Direct Current Drains to Remote Earth

The most common method is draining current to remote earth through a grounding system with a single diode junction, but locations with isolation joints may more efficiently force the current through diode junctions (see Figure 5-2 and Figure 5-3) to remote earth.

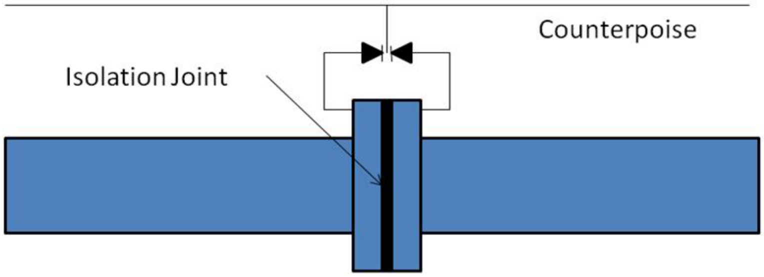


Figure 5-2
AC mitigation through isolation joints using diode junctions

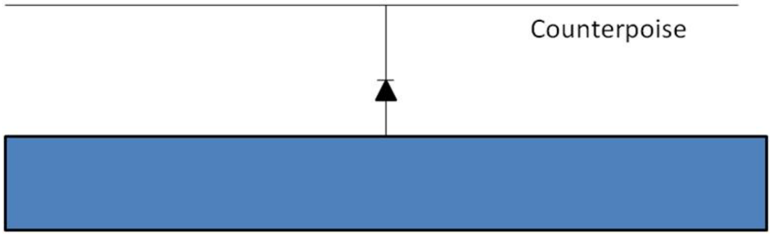


Figure 5-3
AC mitigation through a single diode junction

Galvanic Decouplers

Galvanic decouplers may be used to allow passage of alternating current while blocking stray direct current (see Figure 5-4). Both solid state and analog models are commercially available (Dairyland & ELK Engineering).

Figure 5-4
Galvanic decoupler (Dairyland) for dc corrosion mitigation

Designs for deep groundbeds may allow drainage of some stray currents by providing low resistance to remote earth (see Figure 5-5). Engineered backfills will augment the groundbed design by reducing electrode-to-soil resistance, allowing more consistent current distributions, and holding moisture during dry intervals.

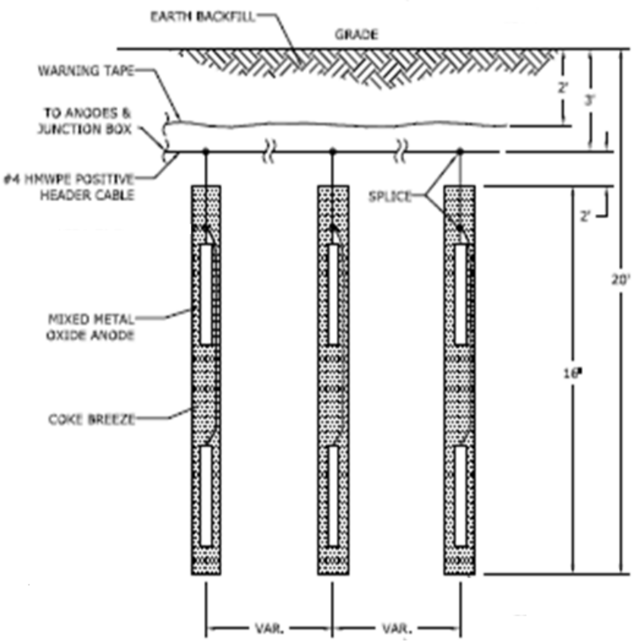


Figure 5-5
Deep ground bed design

Cathodic Protection

Cathodic Protection consists of deliberate methods that use selected materials and/or the application of direct electrical current to counteract the normal corrosion of a structure that contains metal, such as an underground petroleum storage tank or natural gas pipeline. The fundamental principle of cathodic protection is the application of a counter potential to prevent the electrochemical interchange of ions that occurs in corrosion. On new structures, CP can help prevent corrosion from initiating; and for existing structures it can slow the growth of existing corrosion (see Figure 5-6).

Figure 5-6
Dual rectifiers installed at the Charlotte Underground Transmission Test Facility

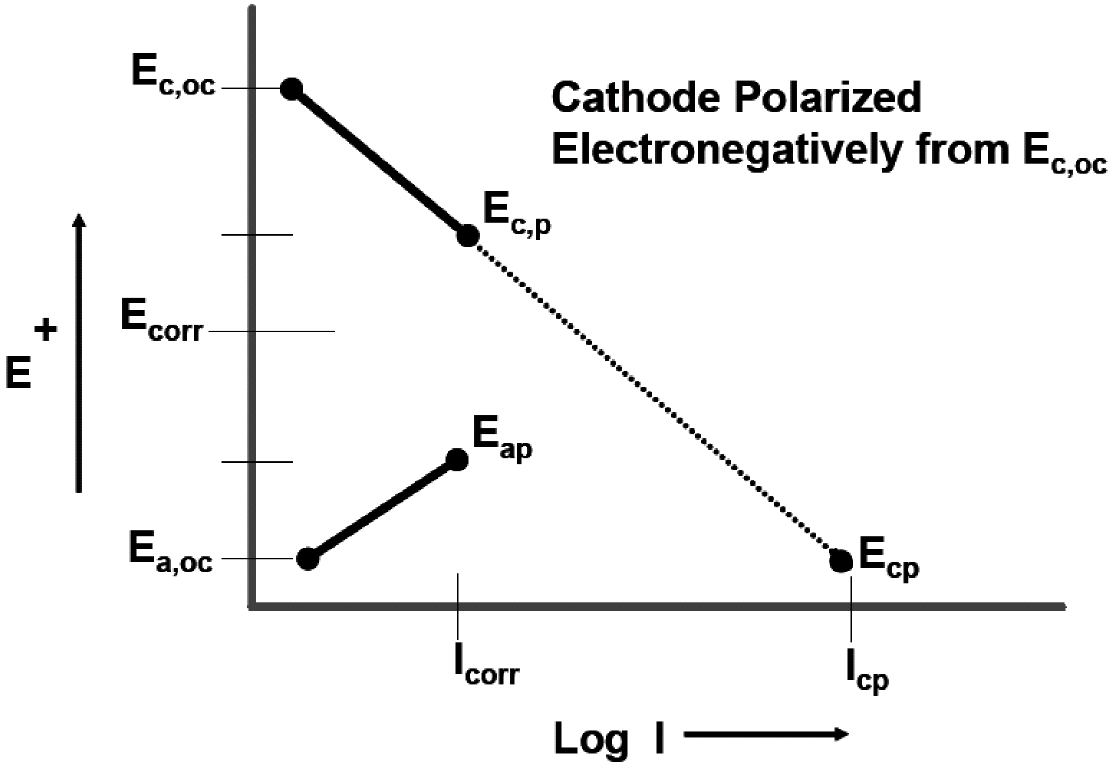


Figure 5-7
Cathodic site is shifted to the same negative potential as the anodic site

Types of Cathodic Protection

The basic two methods of cathodic protection are the sacrificial anode system, which is a passive system, and the impressed current system, which is an active system. The sacrificial anode system takes advantage of the natural potential difference between dissimilar metals. Corrosion can be prevented by coupling a metal with a more active metal when both are immersed in an electrolyte and connected with an external metallic path (sacrificial anode) or by having a source of direct current electricity to interfere with the activity of the electrochemical cell responsible for corrosion (impressed current). The metal being protected becomes a cathode, hence the name cathodic protection.

Whether using an impressed current method or the sacrificial anode method, cathodic protection is essentially the same from the standpoint of the structure being protected. Both cathodic protection systems supply high-energy electrons to the structure being protected, and in both the circuit of the electrochemical cell is completed through the soil. These two systems are described in the following sections.

Environmental Factors Governing Polarization

Environmental factors such as pH, temperature, oxidizers, and movement or velocity at the structure surfaces will effect polarization. Increased acidity will increase the corrosion rates due to the increased concentration of reducible hydrogen ion (H+) according to the reaction:

$$H^+ + e^- \Rightarrow H$$

The pH of an electrolyte—soil in the case of a transmission structure—is rarely neutral. This is due to the presence of ionic species in the electrolyte from the hydrolysis of various types of salts. Salts can also shift the pH balance in either direction, but the end result is reduced soil resistivity and elevated corrosion rates.

Temperature also acts as a depolarizer due to the increased rate of diffusion of reducible species at the cathodic site. This effect is known to decrease the concentration polarization. As the reduction rate at the cathodic site is increased, the polarization level is reduced and the current required for cathodic protection is increased.

Oxidizers will increase the current requirements for cathodic protection because of the reduction reaction at the cathodic sites. The oxygen bonds to the hydrogen ions and reduces them to hydroxyl ions:

$$2H_2O + O_2 + 4e^- \Rightarrow 4OH^-$$

Movement at the cathodic site surfaces acts as a depolarizer, because of the increased availability of reducible species and the increased rate in the reduction reaction.

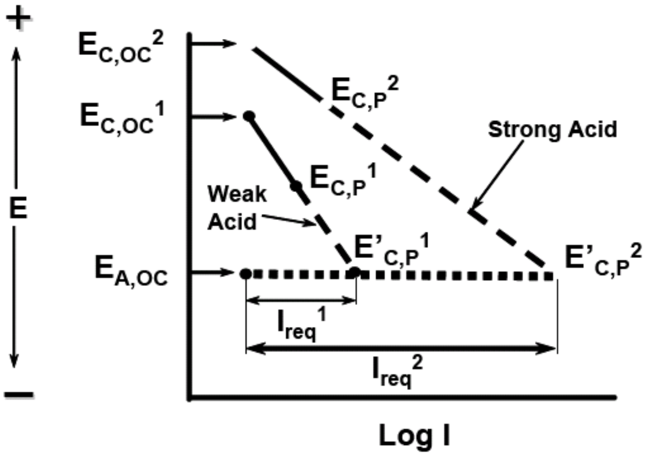
Environmental Factors Affecting Cathodic Protection

The environment can dramatically alter the effectivity of a cathodic protection system. Certain factors such pH, temperature, and soil resistivity should be taken into account in the design stages, but oxidizers and velocity in a water environment will also reduce the efficiency of a system.

An increase in acidity accompanies the increase in reducible hydrogen ions (H+) according to the following reaction:

$$H^+ + e^- \rightarrow H$$

This increase in hydrogen ions lowers the pH of the electrolyte to a more acidic condition and tends to act as a depolarizer as shown in Figure 5-8.

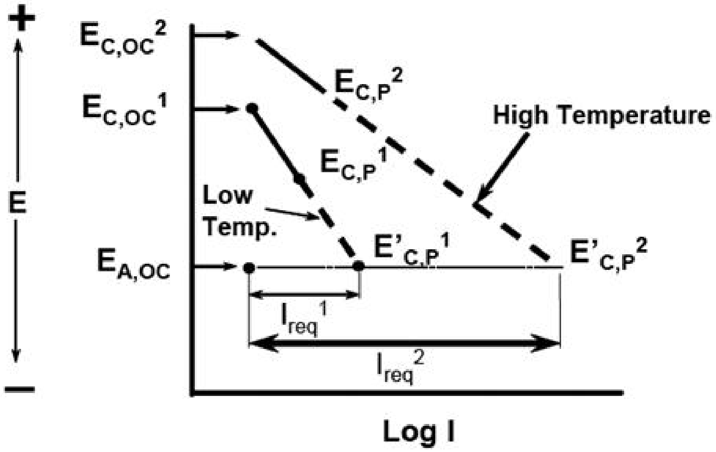


where:

$E_{C,OC}^2$ = Cathode potential, strong acid solution, no corrosion
$E_{C,OC}^1$ = Cathode potential, weak acid, no corrosion
$E_{A,OC}$ = Anode potential
$E_{C,P}^2$ = Cathode potential, strong acid, corroding
$E_{C,P}^1$ = Cathode potential, weak acid, corroding
$E'_{C,P}{}^1$ =CP potential required, weak acid
$E'_{C,P}{}^2$ = CP potential required, strong acid
$I_{req'd}^1$ = CP current needed for weak acid
$I_{req'd}^2$ = CP current required for strong acid

Figure 5-8
pH effects as a depolarizer

Increased temperature depolarizes the metal surface because it decreases the rate of the diffusion of reducible species at the cathodic sites, resulting in a decrease in concentration polarization. Figure 5-9 illustrates the effects of temperature on corrosion rates.



where:

$E_{C,OC}^2$ = Cathode potential, high temperature, no corrosion
$E_{C,OC}^1$ = Cathode potential, low temperature, no corrosion
$E_{A,OC}$ = Anode potential
$E_{C,P}^2$ = Cathode potential, high temperature, corroding
$E_{C,P}^1$ = Cathode potential, low temperature, corroding
$E'^1_{C,P}$ = CP potential required, low temperature
$E'^2_{C,P}$ = CP potential required, high temperature
$I_{req'd}^1$ = CP current needed for low temperature
$I_{req'd}^2$ = CP current required for high temperature

Figure 5-9
Temperature effects as a depolarizer

Geometry Effects on Cathodic Protection

Poles quite often can be polarized with a single anode when it is placed in close proximity to the imbedded section. Lattice structures with grillage foundations quite often require that the anodes be distributed at each leg. The need for multiple anodes is due to soil resistivity and resulting voltage losses between the legs. Other factors in cathodic protection system design include shadowing effects in which the voltage gradients do not extend to the far side of a structure, at least at levels sufficient to provide protection. Steel poles present an additional complexity because the interior of the pole will not be protected from corrosion if the electrolyte doesn't complete a circuit. As a result, the pole must be flooded for cathodic protection system to have any internal effect. Geometric effects on cathodic protection are an area of ongoing research, and anodes of different shapes and sizes must be studied for efficacy.

Impressed Current System

In an impressed current system, an external supply of direct electrical current is used to develop the potential difference between the anode and the structure being protected. A rectifier or other external dc power source instead of the potential difference of the anode with respect to the structure being protected supplies this external current. The external current is injected into the soil (or electrolyte) via engineered anodes. The anodes of an impressed current system provide the means for the protective current to enter the electrolyte; anode consumption is not the primary mechanism for generating the protective current.

Materials such as graphite, high-silicon cast iron, platinum, or mixed metal oxides are used as anodes because they have a very low loss of weight per ampere-year. Voltages of up to 100V and high current densities can be used. Therefore, large areas of structures can be protected by a single anode; and, due to the high driving voltages, the anode can be located remotely from the structure being protected. Figure 5-10 provides a schematic of an impressed current system for a buried pipeline[2].

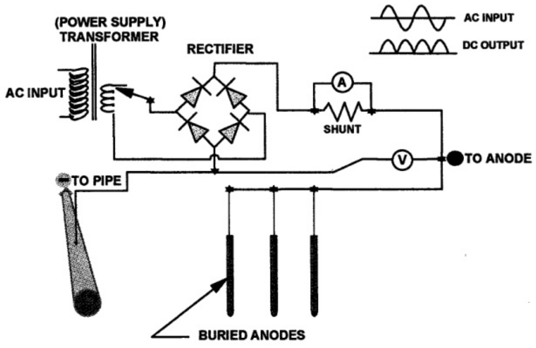


Figure 5-10
Impressed current cathodic protection schematic

Sacrificial Anode Cathodic Protection

Cathodic protection involves the reduction of the potential difference between anodic and cathodic sites to zero, which reduces or eliminates corrosion current flow. Reducing the current flow can be accomplished by impressing current onto a structure from an external electrode and polarizing the cathodic site to the same potential as the anodic site. If there is an interruption in the cathodic protection, the polarization will dissipate and corrosion will recommence. The magnitude of the required current is dependant upon several factors including surface area, soil resistivity, resistance through the structure, and the presence of any depolarizers.

Sacrificial Anode System

The corrosion of an active metal such as magnesium or zinc generates the high potential electrons needed for protection. In this system, the anode material is consumed—sacrificed—in the process, and the anodes must be periodically replaced to maintain continuous protection. The anodes are designed with sufficient anode material so that the anode replacement interval is set at an economically desired number of years. For buried systems, common practice is to design the system for a 10- to 15-year anode life. For systems where anode replacement is difficult (expensive), longer (20- to 30-year) anode life is often used as design criterion.

The structure-to-electrolyte potentials required for protection with a sacrificial anode cathodic protection system are identical to those for impressed current cathodic protection systems. Due to the limited driving potential of sacrificial anodes, they must be located close to the structure being protected. For the protection of underground structures such as pipelines, the anodes are not usually attached directly to the structure, but are placed in the soil, evenly distributed a short distance from the pipeline, and connected to the pipeline by a wire, usually through a test station. The application of galvanic anodes is limited by the small potential difference (normally less than 1 Volt dc) that can be obtained. Galvanic systems can only be economically used on small or well-coated structures in low-resistivity electrolytes. Since the amount of cathodic protection depends on the current density supplied to the protected structure, the electrolyte resistivity determines the amount of current that the limited voltage will supply; and the amount of metal exposed to the electrolyte determines the amount of current required. Uncoated structures may require an exorbitant number of anodes for adequate protection. In higher resistivity electrolytes, the small anode-structure voltage difference would yield (via Ohms law) an extremely small amount of anode current, hence requiring a large number of anodes. High purity magnesium anodes have the highest potential available; but in high resistivity soil, they would not supply sufficient current to protect a structure unless it had an extremely good coating.

Components in a Sacrificial Anode System

Anodes for Sacrificial Anode Systems

Active metals such as zinc, aluminum, and magnesium are used as sacrificial anodes. The driving potential of these anodes is dictated by the galvanic series and the proximity to the structure material. These active metals, when interconnected with iron or steel in an electrochemical cell, provide the required protective current. The sacrificial anode is consumed at a rate proportional to the current delivered plus any localized corrosion action.

The chemical makeup of the anode material determines the efficiency of the sacrificial cathodic protection system. An anode material that is more positive to the structure that requires cathodic protection will provide a more efficient protection[1].

Table 5-1
Properties of sacrificial anodes
Courtesy of Galvotech

Anode Material	Density (lb/in^3)	Potential (Volts)	Consumption Rate (Ampere-hrs per lb)	Current Density (A/ft^2)
Zinc	0.2565	-1.10	335-354	0.04645
Aluminum	0.097544	-1.10 to -1.15	1040-1290	0.05574-0.2323
Magnesium	0.061416	-1.4 to -1.8	250-580	0.139-0.52

The materials used for sacrificial anodes are either relatively pure active metals such as zinc, magnesium, or aluminum or alloys of these metals that have been specifically developed for use as sacrificial anodes. The selection of a particular anode metal largely depends on the required voltage and resistivity of the electrolytic environment.

Zinc

Because of its high density (over four times that of magnesium and 2.6 times that of aluminum), zinc anodes are much smaller and have higher resistance to electrolyte than magnesium and aluminum. In addition, they have lower voltage potentials. Therefore, zinc anodes are better in soils with lower resistivities, typically soils below 1000 ohm-cm, saltwater, or brackish water.

Zinc anodes deliver up to 90% of the current required to electrolyze a given weight of anode. The remaining 10% is lost due to due to localized anodic action. Zinc anodes are made of pure cast zinc or, in some cases, zinc with a small amount of aluminum and cadmium. Iron in zinc, even in minute quantities, causes the formation of a dense coating that inhibits current flow. The addition of aluminum and cadmium counteracts this effect.

Zinc used for soil anodes should be high-purity zinc, which is at least 99.99% pure zinc. Zinc is not subject to significant anodic polarization when used in suitable backfill. The current efficiency of zinc is reasonably constant from low to very high current outputs in terms of mA/ft2 of anode surface. Zinc has an open circuit potential to a copper/copper sulfate half-cell of –1.1 Volts. If the steel structure is to be protected to –0.85 Volts, the driving potential is only 0.25 Volts. Due to the net driving potential and high density, zinc anodes in soil should have long slender shape. Zinc anodes are commonly available in weights from 5 pounds (2.3 kg) to 250 pounds (113.4 kg) in the form of plates, bars, rods, and ribbons. Zinc should not be used in environments when the pH is over 8 or where the temperature is over 120ºF (49ºC) as in these conditions zinc becomes cathodic rather than anodic to the structure being protected. Zinc anodes are available as bare zinc anodes or packaged in backfill consisting of gypsum and bentonite.

Magnesium

Magnesium is the most widely used metal for sacrificial anodes due to cost and effectiveness. It is particularly excellent in high resistivity soils and in fresh water, brackish water, and seawater applications. Magnesium is more active than zinc and produces greater potential, but is therefore subject to more localized anodic action. As a result, the loss due to the localized activity could be anywhere from one to four times that used for cathodic protection. Magnesium anodes are better in soils with higher resistivities. The higher potential of magnesium results in a higher maximum allowable resistance for the ground bed in comparison to zinc anodes.

Magnesium anodes are available as castings and extrusions weighing from 1 (0.45 kg) to 200 pounds (90.7 kg) and in a wide variety of shapes such as bars, rods, and ribbons. Magnesium anodes may be alloyed with aluminum up to 6% and with zinc up to 3%. Sometimes the anodes are coated with polyvinyl chloride or packaged with a specially designed molded plastic box to improve the current distribution and increase the life of the anode.

Magnesium anodes are also used for the protection of the interiors of water tanks and heaters, heat exchangers, condensers, and waterfront structures. High potential magnesium alloys are available that could raise the potential levels with iron or steel structure from 0.7V to 0.9V (a 28% increase).

The life of magnesium anodes is affected by the current density, electrolyte (water), and backfill.

The current output is reduced to less than 300 amp-hr/lb (660 amp-hr/kg) when operating under low-current densities. The relatively high potential of magnesium favors its use in water applications such as domestic water tanks.

Aluminum

Due to aluminum's lower driving potential and higher current capacity, it is well suited in applications with low resistivity applications, such as seawater. To reduce the passivating effect (oxide film formation on the aluminum surface), aluminum is typically alloyed with mercury or indium. The output of an aluminum anode ranges from 390 to 1250 ampere-hour per pound depending on the alloying. Aluminum is often alloyed with zinc to improve its current efficiency; and, when alloyed with 5% zinc, aluminum anode produces 675Ahr/ lb. Aluminum anodes are used with a lime-salt, salt-calomel, and magnesium oxychloride as backfill. Aluminum anodes alloyed with mercury cannot be used in brackish water or silt/mud.

Design Considerations

Technical and economic benefits should be considered in designing an appropriate cathodic protection system for a given structure or a group of structures. Before preparing the design, basic information is obtained regarding the structure and its external environment by conducting selected field tests and considering the corrosion-control experience of other operations in the general area. In addition to field measurements, historical data concerning the site and other structures located at or near the site of the system to be designed, for example, soil resistivity measurements, plans, and drawings, should be reviewed. In general, specific field determinations of several parameters need to be determined in order to design an effective cathodic protection system.

The objective of the predesign phase is to determine the viability of cathodic protection as an effective means of corrosion control. Once the tentative system components are selected, technical and economical life cycle costs are calculated. After the design is completed, plans and specifications are developed, and the system is installed.

Soil Resistance

Soil resistivity at the structure site can be used in designing the cathodic protection system. The soil's corrosiveness is classified on the basis of resistivity. When soils have resistivities greater than approximately 50,000 ohm-centimeter, corrosion is negligible and cathodic protection is not needed. When soils have resistivities below approximately 10,000 ohm-centimeter and when other soil data indicate that the soil may be corrosive, cathodic protection is needed. If the soil resistivity is between 10,000 and 50,000 ohm-centimeter or is not uniform, further investigations are required to establish whether cathodic protection is necessary and, if it is, what the protection requirements at various locations are. These measures include using test coupons to determine actual corrosion rates and installing test stations on the underground structure to facilitate the taking of potential measurements. Soil resistivity and potential measurements can be evaluated together to determine corrosion rates.

Soil resistivity testing can be done in the area of a proposed anode bed to locate an area of low resistance to place the anodes. Care must be taken to ensure that the low resistance area is not continuous to the protected structure. Poor current distribution may occur if this condition occurs. In some cases, the best location for an anode bed may be in higher resistivity earth. The resistance of the anode bed can be lowered by adding additional anodes, using longer anodes, or increasing the spacing of the anodes. The anodes may have individual leads connected to a header cable or they may be installed on a continuous cable.

Basic Design Procedure for Sacrificial Anode Systems

For sacrificial anode systems, the total current required needs to be determined either from actual current requirement measurements or by multiplying a typical current requirement by the surface area of the structure, bearing in mind that the soil resistivity at a given site is an important factor in the design of a cathodic protection system. The output of the sacrificial anodes to be used can then be determined. The number of anodes is calculated 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.), zinc at 26 lb/A-yr. (11.8 kg/A-yr), and typical aluminum alloy anodes at 11 lb/A-yr (5 kg/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.

An alternate design method that has been used very effectively by the electric utilities is to construct a graph showing the number of anodes required as the soil resistivity varies. These installation templates are structure specific and must be modified when various footer configurations are employed. This method streamlines the installation process by allowing the crew foreman to determine the soil resistivity *in situ* and immediately calculate the required number of anodes from a construction guidebook. A quality control inspection is then scheduled for the next rainy season at which time crews confirm or augment the installation.

Analysis of Design Factors

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

- Anode-to-electrolyte resistance. This factor includes a determination of electrolyte resistivity, resistance (output) of a single anode, the effects of anode configuration and spacing, the effects of anode orientation, and the location of the anodes with respect to both the structure being protected and other metallic structures in the area.
- Weight of anode to give the required anode life.
- The use of special backfill surrounding the anodes. Special backfills are usually justified by increased anode efficiency and should be used unless they are shown not to be economically justified. Backfill is not required when anodes are hung in water or installed at the bottom of bodies of water.
- Seasonal variations. The effect of seasonal variations in electrolyte resistivity from variations in soil conductivity due to moisture or in seawater due to runoff needs to be considered.

Vulnerability to Physical Damage

Anode leads should be trenched to the structure and brought above grade on a side that is sheltered from right-of-way (ROW) maintenance activity. Lattice towers should have the leads brought up on the inside of the post leg and attached above the vegetation level. The anode beds themselves should always be located within the tower footprint if possible due to agricultural activity around the site.

Testing and Maintenance

A variety of methods exist for determining whether a structure is being effectively protected by a cathodic protection system. Since corrosion and cathodic protection are electrochemically based, the test practices are also electrochemically based. The performance of a cathodic protection system can be monitored by measuring the potential of the structure or current input or both. The potentials of the surfaces of a structure with respect to a reference electrode are the most widely used criteria for determining whether or not a structure is being effectively protected by a cathodic protection system.

In addition to the potential survey methods, physical and visual inspections are used to determine the actual condition of the structure being protected. If the surfaces of the structure are accessible, inspection of the structure can be used to determine whether or not it has had effective protection in the past. If an inspection of the structure shows no evidence of corrosion in an aggressive environment, then it can be inferred that the cathodic protection system has been functioning adequately over the long period. For buried or submerged systems where physical access is restricted, the polarized potential survey criteria are the most widely applied.

Sacrificial Anode System Survey

Anode connections to the structure should be inspected to ensure continuity. The sacrificial anode potential check is performed to determine the anode's operational status for buried structures. It is normally conducted as part of the initial cathodic protection survey. The potential of the structure relative to the reference electrode located directly over the structure is measured adjacent to an anode to obtain a structure-to-soil potential reading. The data should be compared with previous readings.

Loss of anode-to-soil potential indicates failed anode. Loss of anode output current indicates that the anode is being consumed and failure may occur.

Use of Coupons

Coupons can be used as an alternative to visual inspection for areas that are difficult to inspect because of accessibility issues. Coupons are small metal samples similar to the metal being protected electrically that are connected to the structure at critical points. These samples are periodically removed and evaluated to determine the effectiveness of the cathodic protection system. The coupon is sized to simulate a large coating defect, or holiday, that needs protecting. If the coupon is protected by the cathodic protection system current, then there is assurance that the structure is also being protected. This theory assumes that the coupon has a similar potential as that of the structure's holiday or coating defect. It also assumes that a large coating defect represents a conservative potential, that is, one that is more positive as compared to smaller defects. It also assumes that uniform cathodic protection exists around the structure.

Troubleshooting

A typical sacrificial anode system consists of the following components:

- Sacrificial anode
- Anode bed/backfill
- Interconnecting cable
- Test station
- Reference electrode

Problems can occur in each of these components.

Anodes

Sacrificial anodes are typically buried vertically next to the structure and are spaced on 5 or 7 foot centers to maximize anode efficiency. Care must be taken to ensure the connection is made above grade and does not come in contact with the soil or grasses near the footing.

Anode Beds

Anode beds affect the effectiveness of the cathodic protection system. If there is not sufficient moisture in the soil, the soil electrical resistance increases, which would require higher voltages to provide the same cathodic protection. Any soil movement may cause breakage of the connections between the conductors and the anodes.

Under Protection

If the measured potentials of the structure are not as negative as required by one or more of the applicable criteria for cathodic protection, some corrosion of the structure may occur. However, the corrosion of the structure will be reduced in proportion to the amount of current supplied. When protective currents are totally interrupted, corrosion will usually return to a normal rate after a short period of time.

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 major components in a sacrificial system are the anode and the structure lead. 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 cause of this lack of protection.

Sacrificial Cathodic Protection Troubleshooting

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

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 sacrificial cathodic protection systems, maintaining the dielectrics of the structures 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, require a very low current flow. Metals that are not well coated and have a low contact resistance with the soil will require more protective current and deplete the anode on an accelerated basis.

Areas needing additional guying should have fiberglass insulating rods installed to eliminate the need for additional anodes. An increase in protected surfaces area can raise the polarization level to allow corrosion to occur.

Lead Wire

A sudden zero reading for the anode output lead current indicates that the lead wires may have failed. However, anode lead wire failure is uncommon because the anodes cathodically protect the conductor even if it is exposed by nicks or defects in the insulation. Anode leads are often cut by excavations if the leads are not properly identified before digging begins. This problem can be avoided by carefully surveying the areas and locating the lead wires before digging begins. If the wires are cut during digging, they should be repaired before the excavation is backfilled.

Comparison of Sacrificial and Impressed Current Cathodic Protection Systems

In most cases the impressed current system is designed to deliver a relatively large amount of current from a limited number of anodes, and the galvanic anode system is designed to deliver relatively small currents from a large number of anodes. Each method of applying CP has characteristics that make it more applicable to a particular structure than the other. A comparison of these characteristics is provided in Table 5-2.

Table 5-2
Comparison of cathodic protection system characteristics

Galvanic Anode System	Impressed Current System
No external power required	External power required
Fixed driving voltage	Adjustable voltage
Fixed current	Adjustable current
Limited current capacity (10-50 mA typical)	Higher current capacity (10-100 Amperes typical)
Used usually in low resistivity electrolytes	Can be used in low to high resistivity electrolytes
Usually used with small or well coated structures	Can be used on any size structure
Low unit cost	High unit cost
Low maintenance	Higher maintenance
Does not cause stray current interference	Stray DC currents can be generated

Regardless of the type of system used, current flows from the anode through the electrolyte (soil or water) to the structure to be protected. Where the current flows onto the structure from the surrounding electrolyte, the potential of the structure is made more negative. CP is achieved when this change in potential is sufficient to arrest corrosion. NACE SP0169-2007 provides acceptance criteria for cathodic protection of underground or submerged metallic piping systems and can be used as a basis for cathodic protection of embedded steel tubular structures.[3] External corrosion control can be achieved at various levels of cathodic polarization depending on the environmental conditions. However in the absence of specific data that demonstrate that adequate CP has been achieved, one or more of the following criteria shall apply:

1. A negative (cathodic) potential of at least 850 mV with cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte and is considered an "On" potential with CP current applied. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.
2. A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode. The polarized potential or "Instant-Off" potential is taken immediately after the CP current is interrupted.
3. A minimum of 100 mV of cathodic polarization between the structures surface and a stable reference electrode contacting the electrolyte. The formation or decay can be measured to satisfy this criterion.

In order to prevent corrosion using cathodic protection, current must flow continuously through the electrolyte and onto the structure surface at all locations. If a portion of the structure does not receive current, the normal corrosion activity will continue at that point. Uneven distribution of current to a structure surface as a result of a high resistivity bedrock layer or outcrop is an example of shielding, which will compromise CP system performance.

6

CONCLUSIONS

A well-protected pipe-type cable transmission line will utilize various protection systems to address specific maintenance issues. An integrated approach would entail a condition assessment, validation of the results, and then a prescribed remedial action based upon the findings. Actions could encompass coating system repair, cathodic protection, and ac or dc mitigation methods.

All of these techniques are limited by the environment (urban or rural) and type of event (static or dynamic). The solutions then become limited to non-invasive methods or technologies to identify the presence of stray currents and mitigation methods for drainage or cathodic protection.

New sensor arrays may be placed in strategic locations to provide streaming data such as corrosion rates, measurements of environmental factors such as temperature, moisture, pH, REDOX or soil resistivity and to monitor health indices such as structure-to-soil potentials.

These sensor technologies may also provide frequencies and amplitudes of dynamic stray current waveforms, and new inverter-based rectifier systems may be designed to provide active waveform cancelation through signature recognition. These new systems may provide a solution to limitations of constant potential rectifiers that are affected by response times and heavy potential swings.

Because there is a high probability of issues developing as systems age, it is wise to incorporate safeguards during the design phase, capitalize the additional costs, and optimize the designs through an expanded geophysical survey. An expanded geophysical survey would include corrosion rate measurements, soil resistivity profiles, ground water measurements, and a study to identify dynamic and static stray currents.

7

FUTURE WORK

Pipe-type cable systems are aging; and gaps have been identified in the design, operation, and maintenance of pipe-type cable systems. One gap is in the area of inspection and assessment tools or technologies required to provide a condition assessment of the pipe. Another gap area is the cost of oil testing for contaminants generated during operation. These contaminants are carbon-chain gases that are disassociated due to thermal stresses within the cooling oil and may be become identifiable through the development of specific sensors.

Future research will include evaluation of new and emerging inspection technologies, but also deployment of sensors developed in the Charlotte corrosion laboratory. These sensors are designed to discriminate between pitting and general corrosion, measure corrosion rates, identify gasses in oil suspension, and measure various environmental factors such as moisture, temperature, pH, REDOX, and structure-to-soil potentials.

Installation of sensor arrays may be possible as a retrofit near manholes and vaults to monitor change at the penetration points. Future work may also include:

- Installation of permanent guided wave collars to monitor spans between manholes for changes in pipe sectional loss
- A major effort to develop active-waveform-cancelation cathodic protection rectifiers that can identify and cancel stray currents using a library of waveform signatures
- Sensors to identify the presence of various gasses associated with aging cooling oil

8

REFERENCES

1. Peabody, A.W. (edited by Bianchetti, R.L.), Control of Pipeline Corrosion. 2nd Edition Houston, TX: NACE International. 2001.
2. *Corrosion of Buried Steel Pipes used with Transmission Pipe-Type Cable Systems*. EPRI, Palo Alto, CA: 2009. 1017731.
3. NACE SP0169-2007, “Control of External Corrosion on Underground or Submerged Metallic Piping Systems” (Houston, TX: NACE International).
4. ASTM G106 - 89(2004), “Standard Practice for Verification of Algorithm and Equipment for Electrochemical Impedance Measurements” (West Conshohocken, PA: ASTM International).

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

10xxxxx

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com