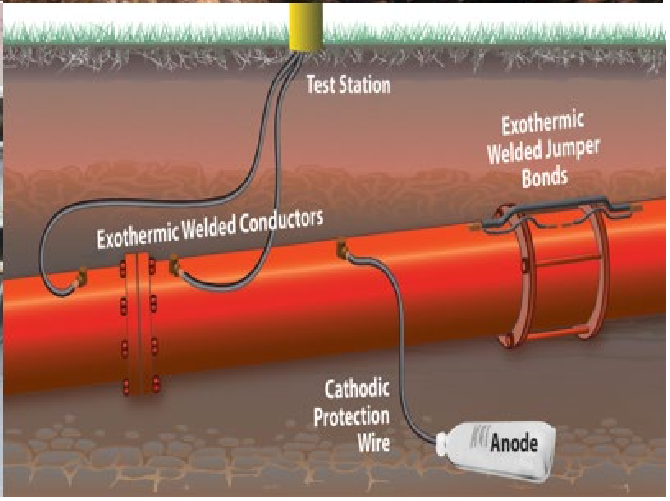
BUREAU OF
RECLAMATION

Facilities Instructions, Standards and Techniques - Volume 4-5

Corrosion Protection



U.S. Department of the Interior

May 2024

This page intentionally left blank.

Facilities Instructions, Standards, and Techniques - Volume 4-5

Corrosion Protection

Prepared by

Power Resources Office
and
Technical Service Center

U.S. Department of the Interior
Bureau of Reclamation
Power Resources Office
Denver, Colorado

May 2024

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, Native Hawaiians, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Table of Contents

Figures Page

Photographs Page

Tables

Codes and Standards

ASTM B418, Standard Specification for Cast and Wrought Galvanic Zinc Anodes
ASTM B843, Standard Specification for Magnesium Alloy Anodes for Cathodic Protection
NACE/ ASTM G193, Standard Terminology and Acronyms Relating to Corrosion
NACE SP0100, Cathodic Protection to Control External Corrosion of Concrete Pressure Pipelines and Mortar-Coated Steel Pipelines for Water and Wastewater Service.
NACE SP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems.
NACE SP0193, External Cathodic Protection of On-Grade Carbon Steel Storage Tank Bottoms.
NACE SP0196, Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks.
NACE SP0285, Corrosion Control of Underground Storage Tank Systems by Cathodic Protection.
NACE SP0286, Standard Practice Electrical Isolation of Cathodically Protected Pipelines
NACE SP0290, Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures.
NACE SP0388, Impressed Current Cathodic Protection of Internal Submerged Surfaces of Carbon Steel Water Storage Tanks.
NFPA 70, National Electric Code

Reclamation Standards and Documents

FAC 01-04	*Review of Operation and Maintenance Program Examination of Associated Facilities (Facilities Other Than High- and Significant-Hazard Potential Dams)*
FAC 01-07	*Review/Examination Program for High and Significant Hazard Dams*
FAC 04-01	*Power Review of Operation and Maintenance (PRO&M) Program*
FAC 04-14	*Power Facilities Technical Documents*
FAC P04	*Hydroelectric Power*
FAC P14	*Power Operations and Maintenance (PO&M) Technical Standards*
FIST 1-1	*Hazardous Energy Control Program.*
FIST 2-5	*Turbine Repair*
FIST 2-6	*Auxiliary Mechanical Equipment*
FIST 4-1A	*Maintenance Schedules for Mechanical Equipment*
FIST 4-1B	*Maintenance Schedules for Electrical Equipment*
MERL-2011-35	*Guidelines for Reporting Corroded Pipe*
MERL-05-19	*The 10% Soil Resistivity Method*
MERL-2013-39	*Corrosivity Testing of Waters and Soils*
RCD 03-03	*Request for Deviation from a Reclamation Manual Requirement and Approval or Disapproval of the Request*
RSHS	*Reclamation Safety and Health Standards.*

Reclamation Forms

POM: https://teamssp.bor.doi.net/printanddup/forms/POM%20Forms/Forms/AllItems.aspx
POM-226, FIST Revision Request
POM-300, FIST Variance Form
POM-500, Voltage Controlled Rectifier Data Sheet

Acronyms and Abbreviations

A	Amp
ac	Alternating current
AMPP	Association for Materials Protection and Performance (formerly NACE and SSPC)
AWG	American Wire Gauge
°C	Degrees Celsius
CARMA	Capital Asset and Resource Management Application
cm	Centimeters
CSE	Copper/Copper-Sulfate reference electrode
dc	Direct current
D&S	Directive and Standard
EPA	U.S. Environmental Protection Agency
°F	Degrees Fahrenheit
FIST	Facilities Instruction, Standards, and Techniques
ft	Feet
GACP	Galvanic anode cathodic protection
HMWPE	High molecular weight polyethylene
ICCP	Impressed current cathodic protection
IJFK	Isolating joint flange kit
IR	IR drop or voltage drop due to current in resistive path (e.g., soil)
L	Liters
MCL	Materials and Corrosion Laboratory
mV	Millivolts
Mg	Magnesium
mg	Milligrams
MMO	Mixed metal oxide
µS	Microsiemens
NACE	National Association of Corrosion Engineers (now AMPP)
O&M	operations and maintenance
OSHA	Occupational Safety and Health Administration
pH	Potential of Hydrogen
ppm	Parts per million
PRO	Power Resources Office
Reclamation	Bureau of Reclamation
RM	Reclamation Manual
SACP	Sacrificial anode cathodic protection
SOP	Standard Operating Procedures
SSPC	Society for Protect Coatings (now AMPP)
TSC	Technical Service Center
UV	Ultraviolet
V	Volts

Symbols

°	Degree
%	Percent
+	Positive
-	Negative
#	Number
e	Electron
MΩ	Megaohms
Ω	Ohms

1.0 Introduction

The Bureau of Reclamation operates and maintains hydroelectric powerplants, switchyards, pumping plants, water delivery equipment, and associated facilities in the 17 western United States. These facilities house complex electrical and mechanical equipment that must be kept operational because they are critical to the electric power and water delivery systems relied on by many. Facilities, Instructions, Standards, and Techniques (FIST) are technical documents that provide criteria and procedures that should be utilized by the offices involved in managing Reclamation facilities and assets.

This document establishes standard technical practices to ensure the safe, reliable, economic, and efficient operation and maintenance (O&M) of Federal facilities by keeping related assets in good condition and ultimately protecting Federal investments. These technical practices provide a sufficient level of detail to ensure consistent application while providing flexibility for the use of innovative techniques and approaches. This document was developed with input from staff in Reclamation's Denver, regional, and area offices.

1.1 Purpose and Scope

Mitigating corrosion is important from both an operation and cost standpoint. Among other consequences, ignoring corrosion can shorten structure life, increase equipment or system out-of-service time, and increase maintenance. In addition to the dollar cost, the loss of critical material and human effort are important. Countermeasures such as proper coating system and cathodic protection system maintenance techniques help diminish such losses.

This document provides field personnel the basic understanding of corrosion processes and countermeasures to minimize the effects. It will restrict itself to some of the more common forms and mechanisms of corrosion that are likely to be encountered. If additional guidance is needed, see section 1.2 for additional Reclamation resources and support documents.

This volume is applicable to all materials which are subject to corrosion in Reclamation facilities subject to all conditions; atmospheric, submerged, and buried.

1.2 Resources and Support

When detailed information is needed beyond this document, the below Technical Services Center (TSC) Materials & Corrosion Laboratory Services documents should be consulted. The documents may be found on the TSC Manuals & Guides webpage. Technical Service Center | Bureau of Reclamation (usbr.gov)

- Guide to Protective Coatings, Inspection, and Maintenance
- Coal Tar Enamel Repair Guide, Technical Memorandum No. 8540-2017-047

- Guidelines for Field Installation of Corrosion Monitoring and Cathodic Protection Systems, Technical Memorandum No. MERL-2012-40

Different corrosion problems have different solutions; hence the importance of understanding corrosion mechanisms and the proper actions to take. Since this document restricts itself to some of the more common forms and mechanisms of corrosion that are likely to be encountered with ferrous metals in soil and water environments, these scenarios may be addressed using cathodic protection. When faced with an unfamiliar corrosion issue seek aid from TSC or similar corrosion professionals. While this document may not give the reader sufficient knowledge to handle corrosion problems on their own, it will allow them to discuss corrosion more effectively when contacting that professional.

Cathodic protection designs are customized for each application and require specialized knowledge and training. This document will describe methods for using cathodic protection to protect the exterior of immersed and buried structures, site personnel are strongly advised to contact a corrosion professional experienced in cathodic protection before attempting installations. Such personnel include Cathodic Protection Technicians, Technologists, and Specialists certified by AMPP and are available at the Materials and Corrosion Laboratory (MCL) of the Reclamation TSC.

Incorporating corrosion mitigation countermeasures, such as coatings, cathodic protection, and material selection, into the design of a structure at construction is the best and most economical strategy to mitigate corrosion. This approach may require advanced notice to permit corrosivity testing and evaluation, as well as some added construction expense. If not incorporated during the design phase and subsequent significant structural corrosion occurs after construction, the labor, re-mobilizing, possible re-excavating, equipment downtime and related expenses, and design and development of a retrofit system and method can be a significantly greater expense. Involve a corrosion professional as early in the project as possible.

When faced with corrosion damage, a preliminary examination of a structure should be performed to define the extent, severity, and characteristics of corrosion. This information can provide a clue as to what corrosion mechanism is present and/or what further testing may be needed. When reporting suspected corrosion damage, provide such information as:

- The specific alloy involved (e.g., 304 or 316 stainless steel).
- The environment surrounding the damaged structure, including temperature, pH, resistivity (conductivity), chloride content, and any other such information that may already be available.
- The appearance of the damage (e.g., pitting, general corrosion, cracking, etc.).
- The type and condition of any protective coatings.
- Photos of the area in question.

While many of the assets in Reclamation are accessible for internal and external inspections, many are not. Inaccessible systems include Auxiliary Piping systems discussed in FIST 2-6, *Auxiliary Mechanical Equipment*, certain embedded pipes and rebar, and certain areas of a dam. When possible, it is recommended to have a condition monitoring program which uses non-destructive examination techniques to monitor the long-term health of the piping system. In certain systems leaks can be your first sign of corrosion issues. It is recommended to report pipe corrosion damage using the Failed Pipe Reporting Form (POM-503) and in accordance with MERL-2011-35 *Guidelines for*

Reporting Corroded Pipe to help with root cause analysis and improve future facility maintenance. The use of this form should not be limited to auxiliary piping systems, other structures exhibiting corrosion damage should be reported in a similar manner.

1.3 Reclamation Standard Practices

FIST manuals are designed to provide guidance for maintenance and testing on equipment in Reclamation's facilities. There may be multiple ways to accomplish tasks outlined in this document. Facilities may exercise discretion as to how to accomplish certain tasks based on equipment configurations and available resources.

Reclamation's regions, PRO, and TSC agree that certain practices are required to be consistent across all Reclamation facilities. Mandatory FIST procedures, practices, and schedules that appear in **{Red, bold, and bracketed}** or **[Black, bold, and bracketed]** text are considered Reclamation requirements for the O&M of equipment in power facilities. RM D&S FAC 04-14, *Power Facilities Technical Documents*, describes the responsibilities required by text designations: **{Red, bold, and bracketed}**, **[Black, bold, and bracketed]**, and plain text, within this technical document. Refer to RM D&S FAC 04-14 for more details concerning technical documents.

1.4 Maintenance Tables

Maintenance tables for tasks described in this document are included in FIST 4-1A, *Maintenance Scheduling for Mechanical Equipment*.

1.5 Manufacturer Recommendations

The information in this document is based on manufacturers' documentation and historic Reclamation practices. Due to the differences in equipment designs, owner's manuals and manufacturer's recommended maintenance should be consulted when developing job plans. Not following the manufacturer's guidance may void the warranty of new equipment. If there is a discrepancy between the FIST and the manufacturer's recommendations, the job plan must use the more stringent practice unless there is a reason that a less restrictive maintenance practice is warranted. Use of a less restrictive maintenance practice must be approved as outlined in RM D&S FAC 04-14 by either a deviation or a variance. A deviation maybe granted in accordance with RCD 03-03 and FIST Variance form (POM-300).

1.6 FIST Revision Requests

The FIST Revision Request Form (POM-226) is used to request changes to a FIST document. The request will include a summary of the recommended changes and a basis for the revision or new FIST. These forms will be submitted to the Manager, PRO. The PRO Manager will keep a list of Revision Requests for each FIST and include these in the next scheduled revision unless the change is prioritized sooner.

2.0 General

2.1 Corrosion Terms

Appendix A at the end of this document is provided to define corrosion, along with a number of corrosion-related terms frequently used in corrosion work. Several are described more in terms of practical corrosion concepts rather than as formal definitions. NACE/ASTM G193*, Standard Terminology and Acronyms Relating to Corrosion* contains additional definitions.

2.2 Forms of Corrosion

Corrosion, though commonly associated with metals, can affect any construction material and takes many forms. Corrosion of metals occurs as a result of their tendency to revert to the lowest-energy state—for many metals, this is an ore. Commonly identified forms associated with corrosion of a metal in an electrolyte are discussed below.

The reader may also see other classifications, such as microbially-induced corrosion. In addition, many of the listed forms of corrosion have sub-categories for specific cases or for a specific metal. A full treatment of each type of corrosion and its intricacies is beyond the scope of this document. For additional information, check Principles and Prevention of Corrosion (Jones, D. A., 1992).

2.2.1 General Corrosion

Oxidation of the metal exposed to an oxidizing environment (e.g., water, humid air, etc.) results in surface corrosion and relatively even metal loss over the surface of the structure.

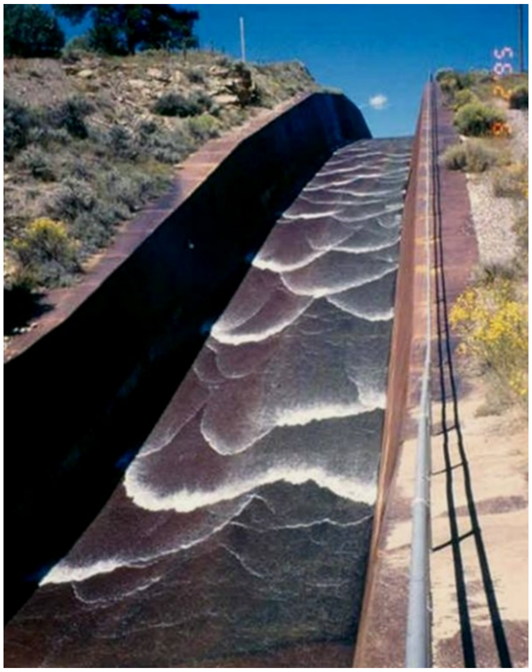


Photo 1. General corrosion on a spillway

2.2.2 Galvanic Corrosion

Galvanic corrosion can occur when two dissimilar metals are physically or electrically connected causing accelerated corrosion on the more active metal (the anode) while reducing the rate of corrosion on the other more passive metal (the cathode). Connecting new rebar or pipe to old rebar or pipe can also result in galvanic corrosion. As shown in Photo , the large cathode to anode area ratio causes corrosion of the anchor despite the protective nature of the high pH mortar.

Photo 2. Galvanic corrosion of a mild steel anchor bolt due to the stainless steel stoplog guide

2.2.3 Concentration Cell

Concentration cell (oxygen, metal ion, pH, etc.) is a limited form of a galvanic corrosion cell where the same metallic structure is exposed to different environmental concentrations in the same electrolyte or a structure transitioning from one electrolyte to another. These situations could include a pipeline being exposed to different types of soil or a metallic structure entering/exiting a concrete encasement where it sees dramatically different pH conditions.

Photo 3. Corrosion of a steel pipe at the concrete/soil interface due to pH cell corrosion

2.2.4 Crevice Corrosion

Crevice corrosion is a localized corrosion at mating surfaces or under deposits due to the trapping of electrolyte and the concentration of oxidizers such as chlorides and an oxygen concentration cell in these locations.

Photo 4. Crevice corrosion on a radial gate access port

2.2.5 Pitting Corrosion

Pitting corrosion is a highly localized corrosion resulting in holes or "pits" in a metallic surface due to localized attack on a small area. Pitting corrosion can be the result of situations such as a localized loss of passivation, coating damage, or stray current interference. A localized loss of passivation could result in a large cathode-to-anode ratio causing an accelerated but localized galvanic corrosion.

Photo 5. Pitting of the interior of the outlet works pipe

2.2.6 Selective Leaching

Selective leaching, also known as dealloying and selective corrosion, occurs in some metal alloys when one component is preferentially removed from the alloy by a galvanic corrosion process leaving a mechanically weak structure with essentially original dimensions. Some materials where this can occur include ductile and cast-iron where the iron is leached from an area on the pipe leaving behind a graphite structure. Photo 6 is an example of selective leaching. When the pipe was tapped with a small rock, holes emerged revealing the loss of strength due to iron leaching.

Photo 6. Failed pipe demonstrating selective leaching.

Erosion Corrosion

Erosion corrosion is a degradation of the surface of a material due to mechanical action such as impingement or abrasion from liquid or slurry. Fluid or particle velocity combines with corrosion to produce synergistic damage through removal of protective oxide layer and exposure of “fresh” surface to electrolyte. Cavitation is one form of erosion corrosion.

Photo 7. Pipe showing how high turbulence flow can cause erosion corrosion

2.2.7 Stress Corrosion Cracking

Stress corrosion cracking occurs when a material which may not typically corrode at a fast rate in the current environment can fail due to the increased stress risers caused by corrosion where the stress, an applied tensile stress or residual stress, becomes great enough to result in crack formation and growth.

Photo 8. Stress corrosion cracking of a steel bell and spigot joint on a pretensioned pipe

2.2.8 Intergranular Corrosion

Intergranular corrosion happens when corrosion occurs along the grain boundaries of a material which is typically resistant to corrosion due to what is known as grain boundary depletion. This can occur in some stainless steels when they are improperly heat treated or during welding; chromium is depleted from the grain boundaries due to the formation of chromium carbide thereby reducing the chromium content and reducing the passive nature of the stainless steel at the grain boundaries.

3.0 Corrosion Principles and Concepts

3.1 Corrosion Cell Concept

The corrosion cell is a way of visualizing the various processes taking place during corrosion. The elements of a corrosion cell a include:

- Anode
- Cathode
- Metallic path for current flow between the anode and cathode
- Electrolyte for ion flow between the anode and cathode

The locations where oxidation (loss of electrons) takes place are called anodes while the locations where reduction (gain of electrons) takes place are called cathodes. As a result of the different reactions involving the giving up of electrons at some locations and accepting of electrons at other locations, the anodes and the cathodes create a potential or voltage difference between them. Current can pass when anodes and cathodes are connected by an electron-carrying path.

General corrosion of a single metal can also be described using this model, as shown in Figure 9. The term ‘mixed potential theory’ was coined to describe it. At any point in time, mixed potential theory visualizes anodic points and cathodic points on a single piece of metal in an electrolyte; the locations of these anodes and cathodes randomly change over time. The result is more or less an even metal loss over the surface.

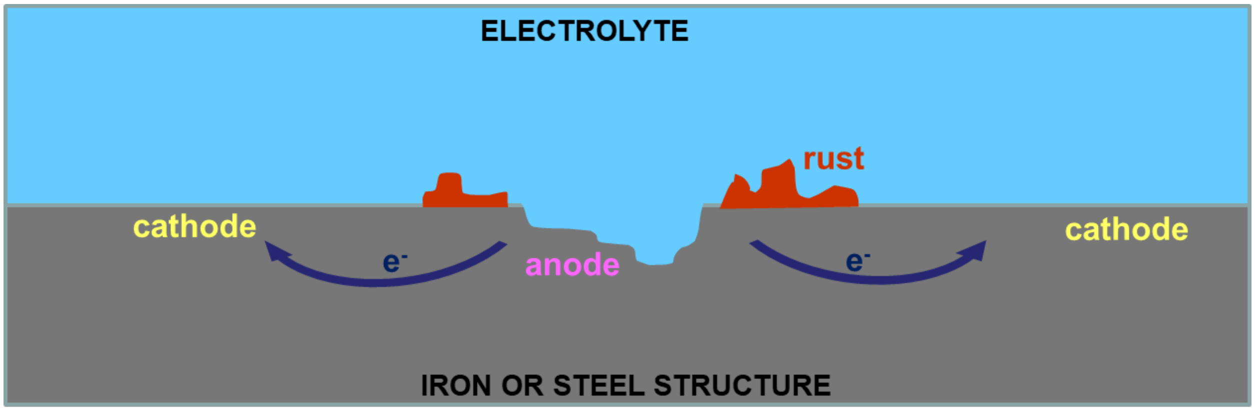


Figure 1. A corrosion cell demonstrating mixed potential theory

The reactions at anodic and cathodic sites change the surrounding chemistry and can affect the corrosion rate and the location of anodic and cathodic sites. Cathodic protection is a purposeful method of changing the voltage difference of anodic and cathodic sites, so that all anodic sites become cathodic.

3.2 Soil and Water Corrosivity

The corrosion of a metal can occur under immersion or burial conditions. Corrosion can also occur on structures in atmospheric conditions due to humidity and condensation. In applicable corrosion nomenclature, soil and water are known as the electrolyte. The electrolyte has several important components or conditions which can increase the corrosion rate including:

1) Increased Oxygen content (e.g., dissolved oxygen)
2) Increased Ionizable chemicals (e.g., chlorides, sulfate)
3) Increased Temperature
4) Decreased Resistivity

These components of the electrolyte can have a strong influence on the corrosivity of the environment. Table 1 lists the corrosivity values for resistivity, pH, chlorides, and sulfates.

Table 1. Corrosivity Categories

	Range	Values
Resistivity (Ω-cm)	Low	>10,000
	Moderate	5,000-10,000
	Severe	2,000-5,000
	Very Severe	<2,000
pH	Acidic	<6
	Neutral	6-9
	Basic	>9
Chlorides (mg/L)	Low	<100
	Moderate	100-500
	Severe	>500
Sulfates (mg/L)	Low	<1,000
	Moderate	1,000-2,000
	Severe	2,000-20,000
	Very Severe	>20,000

The information in Table 1 is based on a number of references that help to specify the ranges of severity in soil and water corrosivity.

Water soluble minerals in soils may be dissolved and transported in flowing water during periods of high precipitation. These minerals could cause adverse reactions with buried or immersed structures, such as sulfate attack in concrete or if the minerals are oxidizing agents, corrosion of metals. For metals in soil or water, corrosion is typically a result of contact with soluble salts found in the soil or water.

Reclamation report MERL-2013-39, *Corrosivity Testing of Waters and Soils,* outlines the procedures the Materials and Corrosion Laboratory (MCL) lab uses for corrosivity testing: sample preparation, measuring pH, and determination of concentrations of chlorides and sulfates in soil and water samples. Resistivity ranges are based on the analytical evaluation of past electrical conductivity (inverse of resistivity) and anion data from soil corrosivity tests. Because electrical conductivity is the combination of all soluble salts, with the predominant salts being sulfate and chloride, it can be plotted in such a way to correlate the low, medium, severe, and very severe ranges of sulfate and the low, medium, and high ranges of chloride.

The most reliable method to determine the level of corrosivity is to perform onsite corrosion testing; this may include field corrosion coupon testing, chemical analysis of the environment, and resistivity testing.

3.2.1 Soil Corrosivity

High soil corrosivity generally coincides with low soil resistivity, an electrical property of materials expressed in ohm-cm. This is because low soil resistivity typically results from high levels of dissolved salts in the electrolyte. However, environments that have a low resistivity because of other chemical constituents may have a reduced probability of corrosion. Concrete, for instance, can have a very low resistivity due to its high alkalinity; however, this high alkalinity yields a less corrosive environment for embedded steel.

Reclamation routinely relies on a soil resistivity assessment as one of several factors when considering corrosivity of soil. The specific method that Reclamation uses is described in Technical Memorandum No. MERL-05-19 (The 10% Soil Resistivity Method). The technical memorandum uses raw field resistance data that has been computer processed using an electrical resistivity imaging inversion routine; this provides a roadmap of resistivities along the buried structure, such as a pipeline.

A statistical treatment is then applied to these resistivity readings; the resultant 10% probability aids in determining the level of corrosivity and the recommended minimum corrosion mitigation measures. Additional data (e.g., chloride or sulfate concentration, etc.) is useful in making mitigative recommendations. A corrosion professional may also employ experience with similar materials in the same or similar soil, if available.

The 10% probabilities are also used to estimate the appropriate resistivity to utilize for cathodic protection design. Resistivities along a pipeline will typically vary randomly by 3 or 4 orders of magnitude from location to location. Individual soil resistivity readings are used in designing cathodic protection systems for isolated metallic structures.

Coordinate with a TSC corrosion professional or engineering geologist/geophysicist when soil resistivity data is needed.

3.2.2 Water Corrosivity

Because of rapid diffusion and convection, bodies of water are often more uniform in composition than soils. However, some variations may still exist, such as the lack of aeration in deep water or when water is purposefully aerated (e.g., airburst).

Chloride content, pH, and electrical conductivity (inverse of resistivity) provide information regarding the potential water corrosivity. Corrosion significantly accelerates at pH values below 5 to

6 (acidic). While pH 4 and below may be considered quite corrosive, even the somewhat less acidic pH waters can be of concern. Chloride levels in the 10s of parts per million (ppm) can raise alarm in some instances (e.g., wetting and drying), and 100 ppm chlorides and higher can be significantly damaging.

Resistivity can be determined via conductivity measurements in the case of direct water samples. Mathematically, conductivity is the inverse of resistivity and is usually measured in micro-siemens per meter or per centimeter (1µS/cm = 1/1,000,000 Ω-cm). More conductive waters are generally more corrosive (e.g., seawater vs. fresh water). As in soil, reliable resistivity (conductivity) readings are essential when designing a cathodic protection system for use in water.

Seek the assistance of a TSC corrosion professional or similar when assessing water corrosivity and designing cathodic protection systems for immersed structures.

3.3 Metal/Alloy Susceptibility

The environment alone does not determine how rapidly metallic materials will corrode. The specific metal or alloy and the corrosion products formed in a given environment have a big influence. Metals and alloys differ in their susceptibility to corrosion dependent upon the exposure environments.

More noble (also called cathodic) metals/alloys exhibit more resistance to corrosion in most environments, whereas the more active (also called anodic) materials will more readily corrode in these same environments.

If a more noble and a more active metal are electrically connected in an electrolyte, the corrosion rate on the active metal will be greater than on its own. An increased separation between metals listed in Table 2 will increase the corrosion rate of the active metal. The anodic metal corrodes more rapidly while protecting the noble metal. This is typical of galvanic corrosion and is the basis for galvanic anode cathodic protection (GACP).

Table 2. Galvanic Series of Metals Exposed to Neutral Soil

Resistant to Corrosion	Material	Potential (V vs. CSE) (approximate)
↑	Carbon, Graphite, Coke	+0.36 to +0.19
	High-Silicon Cast Iron	-0.2
Noble or Cathodic	316 Stainless Steel (passive)	-0.10 to -0.05
	304 Stainless Steel (passive)	-0.13 to 0.00
	Mild Steel in Concrete	-0.2
	Mild Steel (rusted)	-0.2
	Cast Iron	-0.54 to -0.41
	316 Stainless Steel (active)	-0.54 to -0.43
	Mild Steel (clean and shiny)	-0.8 to -0.5
Active or Anodic	Aluminum	-1.05 to -0.9
↓	Zinc	-1.10
	Standard Potential Magnesium	-1.6 to -1.5
Easy to Corrode	High Potential Magnesium	-1.75 to -1.7

A standard reference electrode or half-cell provides a baseline to compare electrochemical potentials of various metals in a galvanic series. A copper/copper sulfate reference cell is commonly used for soil or freshwater testing.

A considerable voltage difference results from electrically coupling two metals widely separated in a galvanic series. This voltage produces a relatively large amount of galvanic potential difference (driving force), indicating large amounts of galvanic corrosion. The more active or anodic metal of the galvanic cell suffers accelerated corrosion while corrosion of the more noble or cathodic metal slows down. On the other hand, metals or alloys close together in the galvanic series produce only a small voltage difference when connected; little galvanic corrosion results. Therefore, immersed or buried metals close together in a galvanic series (e.g., copper and copper alloys) can often be used in direct contact without significant corrosion issues, while widely separated metals (e.g., steel and copper) cannot. However, a number of details need to be considered, including the robustness of the parts, the relative surface areas of exposed metal, etc. As a result, it is not possible to provide a voltage difference between metals which is acceptable in all instances.

There is an important caveat when referring to a galvanic series. A given galvanic series is not totally valid for every environment and temperature. Seawater at room temperature is probably the most common galvanic series environment found in literature. Other environments, temperatures, and conditions could yield different orderings. The only way to be certain is to devise a galvanic series for a specific environment, or to perform confirming tests. Nonetheless, one can often gain a general idea from a given series as to which metal or alloy is likely to be more active or more noble in a couple, and how substantial this difference may be.

Zinc provides a good example for this warning. This metal is considerably more active than steel in the galvanic series of Table 2 and should sacrificially protect steel. However, literature indicates that elevating the temperature above 180 ºF in a domestic hot water tank, especially with such chemicals as nitrates, bicarbonates, or carbonates in solution, can cause the potential of zinc to become more noble than that of steel. When this happens, the steel will sacrificially protect zinc.

Passivation is the mechanism whereby stainless steel, and a number of other alloys are able to resist corrosion in certain environments by way of an oxide film. Some corrosion products can also form an effective barrier that prevents the ability of oxygen and electrolytes from reaching a metallic surface. However, not all corrosion products in all environments form effective corrosion mitigation. The metal and environment need to be compatible. Rust is not an effective barrier in most instances; further corrosion often takes place. Steel rebar in a high pH concrete environment can passivate. However, chloride ions in sufficient quantity will induce passive film breakdown of iron or steel in concrete, as will carbonation of the concrete by dissolved carbon dioxide.

3.3.1 Minimizing Galvanic Corrosion

Galvanic corrosion can be eliminated or minimized in the design process. The following design principles will help accomplish this:

1) Avoid immersing or burying dissimilar metals in direct contact with each other. Galvanic corrosion is less likely to occur on structures in atmospheric service.
2) For buried or immersed applications, select metal combinations that are close together in the galvanic series if they must be connected (e.g., 316 stainless steels with 304 stainless steels). A small voltage difference will result in a reduced corrosion rate.
3) Electrically isolate dissimilar metals from one another in an electrolyte, especially if the voltage difference is significant. When metals are not in direct contact with each other, galvanic corrosion will not occur.
4) Avoid situations where the area of the more anodic metal is relatively small compared to the more cathodic metal (e.g., mild steel bolts fastening a stainless steel stoplog guide). Figure 2 demonstrates this principle. A small anode to cathode area ratio (also illustrated in Figure 10) will result in a more accelerated rate of corrosion of the anode. By making the anode significantly larger than the cathode, the corrosion rate of the anode will be significantly less.
5) Apply a dielectric coating to the more cathodic or noble metal, not just the active one that you expect to corrode. Since coatings can have defects or "holidays," coating the cathode helps maximize the anode to cathode area ratio. Coating only the more active metal can result in deep pits. For example, in a stainless and mild steel pair, coating the stainless steel can prevent the pits from forming in the steel.
6) The more anodic member in a galvanic couple should be robust. This will not eliminate galvanic corrosion, but the anodic member may last longer since it can endure more corrosion before failing.
7) Consider using cathodic protection to control galvanic attack.

Note that dissimilar metal corrosion can only occur if:

- Both metals are in an electrolyte.
- Current can flow between the metals through the electrolyte.
- The metals are in electrical contact, either by direct contact with one another or through a wire or other electrically conductive material.

Photo 9. A steel fastener holding a stainless steel ladder demonstrates undesirable anode (fastener) to cathode (ladder) area ratio

3.3.2 Electrical Isolation

Electrical isolation can prevent a portion of a structure from sacrificing itself in a galvanic couple. It can also isolate a structure under cathodic protection from others that are not intended to be protected. Any additional metalwork electrically connected to the cathodic protection system can be a drain on the system if it is not properly isolated. There are ways to electrically isolate parts:

1) Avoid direct mechanical contact (e.g., bolted surfaces)
2) Avoid metallurgical connections (e.g., wires, welds)
3) Use electrical isolation between parts when contact is required (e.g., flanges)

NACE SP0286 describes the equipment and principles for electrical isolation of cathodically protected pipelines. This specialized equipment (see Figure 2) includes: flange isolation kits which incorporate an isolating gasket, washers, and bolt sleeves; monolithic isolation units for weld applications; and isolating unions for threaded applications. Thick coating systems such as wax tapes have been used in some buried applications to protect the isolating joint flange kit (IJFK) from the soil (see Photo 10). Placing the isolation in a vault instead of direct burial is ideal as it prevents deterioration of isolating materials and improves access should repairs be needed.

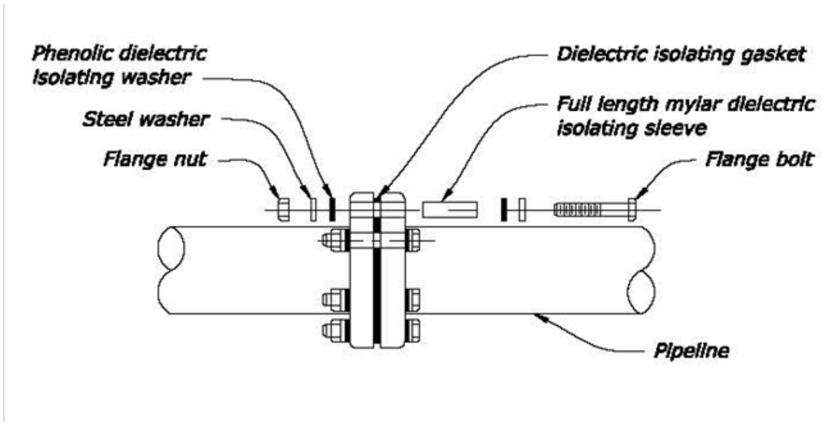


Figure 2. Dielectric Isolating Joint Flange Kit (IJFK)

A typical example of a situation where isolation would be useful is shown in Photo 10. In this case, the yard pipe is connected to the pumping plant manifold, which in turn is electrically connected to the pumps and thus an electrical grounding mat for the plant. If not isolated, then a cathodic protection system would attempt to protect the entire grounding mat and associated metalwork. The drain on the system would be enormous. Therefore, electrical isolation is placed between the yard pipe and manifold, as shown in Photo 10, to isolate the buried section of the yard pipe from the concrete-encased plant side manifold which is more cathodic.

Photo 10. Isolating joints flange kit used to prevent galvanic corrosion of the buried steel pipe

In some instances, there may be a need for alternating current (ac) grounding that conflicts with the need for electrical isolation. If ac grounding is a safety requirement for a metallic structure, then isolation kits can prevent the necessary grounding. Therefore, direct current (dc) decoupling devices can provide a means for allowing ac current, ac fault currents, and even lightning currents to pass while preventing the dc from the cathodic protection system from passing through to the grounding mat or other metalwork. Decoupling devices block the flow of dc current while allowing the flow of ac. Solid-state dc decouplers are the most popular option.

4.0 Protective Coatings

4.1 Coatings

Coatings protect metal from the environment and are the first defense against corrosion. All coatings are designed for specific service environments to protect the underlying metal. Protective coatings typically consist of three components: binder (resin/polymer), pigment, and solvent. In some instances, coatings may leave some components out. For example, a coating comprised of 100% solids materials does not have a solvent. The three generic types of coating materials for protecting metals are:

- **Inhibitive.** Although no longer commonly used, lead and chromates are examples of inhibitive pigments. Coatings containing these pigments provide corrosion protection by passivating the steel surface and preventing oxidation. Zinc phosphate is the primary inhibitive pigment used today.

- **Barrier.** Barrier coatings rely on the coating to form a barrier between the electrolyte and the metal. Examples used today include epoxy, polyurethane, moisture cured urethane, vinyl, vinyl ester, alkyd, polysiloxane, and silicone.

- **Sacrificial.** Sacrificial coatings use pigments or metals that are less noble than the steel substrate, such as zinc or aluminum, and sacrifice themselves to protect steel. Examples used today include zinc rich primers (organic and inorganic), galvanizing coatings, and metallizing coatings.

Note that many of the original coatings applied to Reclamation structures are no longer available. Lead and chromate-based paints and coal tar enamel are no longer used due to environmental and health toxicity concerns. Vinyl coatings have been restricted to impacted immersion use due to changes in the U.S. Environmental Protection Agency's (EPA) volatile organic compounds limits set in the 1990s, but they can still be used if the structure is in impacted immersion service.

In general, most coatings today may not provide a service life as long as the original coatings. It is important to recognize this and to develop and follow a maintenance plan to conduct spot repairs frequently. In addition, it is vital to conduct maintenance on the original existing coatings to provide the longest possible service life.

The TSC is conducting research to understand the mechanisms that allowed the old coating systems to provide long service. The goal is to find alternative coatings with similar properties to attain greater service life.

4.2 Coating Selection

Coatings selection should be determined by the exposure conditions and environmental conditions during application. Selecting the best protective coating can be complicated because each manufacturer has a variety of products to select from. For areas with limited access, a product that can be brushed or rolled is preferred over products that are applied by conventional spray or airless spray equipment. Once a product is selected, you must provide the products safety data sheets to your Safety and Environmental Health specialist and a TSC costings professional to identify safety and environmental process that may need to be adhered to.

- For atmospheric exposure:
    - Good – alkyd/ silicone alkyd, and waterborne acrylics
    - Best – zinc rich primer/ epoxy intermediate/ polyurethane or polysiloxane topcoat, moisture cured urethanes, and galvanizing/ metallizing
- For water immersion:
    - Good – Moisture cured urethanes, epoxy, 100% solids epoxy, vinyl ester, and coal tar epoxy
    - Best – Polysiloxane, vinyl (for impacted immersion only)
- For buried exposure:
    - Good – extruded polyethylene, fusion bonded epoxy, epoxies, and tape with rock shield
    - Best – AWWA C222 Polyurethane
- For invasive mussel control:
    - Best – Silicone foul release coating system
- For erosion / cavitation resistance
    - Good - Ceramic filled epoxy
    - Best - Polyurethane elastomer

Service life is directly related to the level of surface preparation, proper coating selection, and correct application techniques. Site personnel are strongly advised to work with your safety professional and a TSC coatings professional for proper selection and application. No coating system will work in every environment, so there are many different types of coating systems specifically designed for particular service environments. Coatings that exhibit excellent barrier properties (capacitive behavior) provide longer service lives.

Cavitation is the most challenging service environment for coatings. In general, cavitation resistant materials will not last as long as stainless steel weld overlays. Therefore, the guidance is to follow FIST 2-5, *Turbine Repair*. Cavitation resistant coatings and materials could be used to reduce the galvanic corrosion cell that develops with stainless steel overlays or in situations where weld overlays are impractical.

4.3 Coating Defects

There are several types of defects that can occur on a coating during its lifetime. Defects to the coating can occur during the application process or during service when the coating becomes damaged. At this point the coating may no longer provide adequate corrosion protection and needs to be repaired or replaced. Listed below are common types of coating defects with photographs of examples.

4.3.1 Abrasion

Thin areas, gouged areas, or similar defects in the coating or lining caused by mechanical damage from an item being dragged or rubbed on the coating's surface. The damage to the gates shown in Photo 11was from floating debris, such as ice or wood.

Photo 11. Abrasion damage from floating debris

4.3.2 Alligator Cracking

Alligators Cracking is typically seen in coal tar based coatings or linings. The cracks become interconnected and visually similar to alligator skin. Alligator cracking is caused by repeated dehydration and hydration of the material and/or thermal expansion and contraction which creates internal stresses and results in cumulative damage to the coating or lining. Therefore, the service life is greatly influenced by the service environment. The above ground sections of pipe that experience dewatering are expected to degrade more quickly than encased sections. Table 3 provides descriptions and reference to the photos for the five stages of alligator cracking. Photo 12 through Photo 17 show field representations of the different stages. It is important to note that there are no current tests methods to indicate severity of corrosion underneath the coating. Repairs cannot be made to a coating or lining that is alligator cracked and any spot repairs made near a coating that is alligator cracked will have reduced performance. An alligator cracked lining that has hit stage 3, 4, or 5 should be replaced. While the surface of the coating or lining may not change, it is not providing protection to the substrate which is still deteriorating. The full extent of the substrate deterioration cannot be determined until the existing system is removed which can expose pitting or areas of thinning. Predicting the remaining service life of a coating or lining accurately is not feasible due to many contributing factors such as water chemistry, number of outages, weather, and temperatures. Deferring the replacement of a failed coating or lining can result in increased damage resulting in increased cost of future repairs and maintenance.

Table 3. Alligator stages and descriptions

Alligator Cracking	Description	Example Photo	Notes
Stage 1	Fine cracking, no corrosion	Photo 12	Coating/lining is in early-stage failure. Planning should begin for coating/lining replacement, since cracked coating is not repairable.
Stage 2	Fine cracking, minor corrosion in cracks	Photo 13	Coating/lining is close to the end of its service life. Full recoating/relining should be scheduled.
Stage 3	Moderate density cracking, and/or > 50% of cracks contain corrosion	Photo 14	Coating/lining has failed and damage to the substrate is occurring. Specification documents should be drafted for complete recoating/relining.
Stage 4	Moderate-high density cracking, and/or >75% of cracks contain rust	Photo 15	Coating/lining has failed and providing minimal protection to the substrate. Damage to the substrate is occurring. Recoating/relining should be undertaken.
Stage 5	High density cracks linked together, 100% of cracks contain rust	Photo 16 Photo 17	Coating/lining has completely failed and offering no protection to the substrate. Damage to the substrate in the form of material loss and pitting is likely present. Recoating/relining is critical to prevent significant metal loss.

Note - Maintenance options can include either a full recoat/reline or zone repair(s) depending on the condition assessment.

Photo 12. Field representation of stage 1 alligator cracking

Photo 13. Field representation of stage 2 alligator cracking

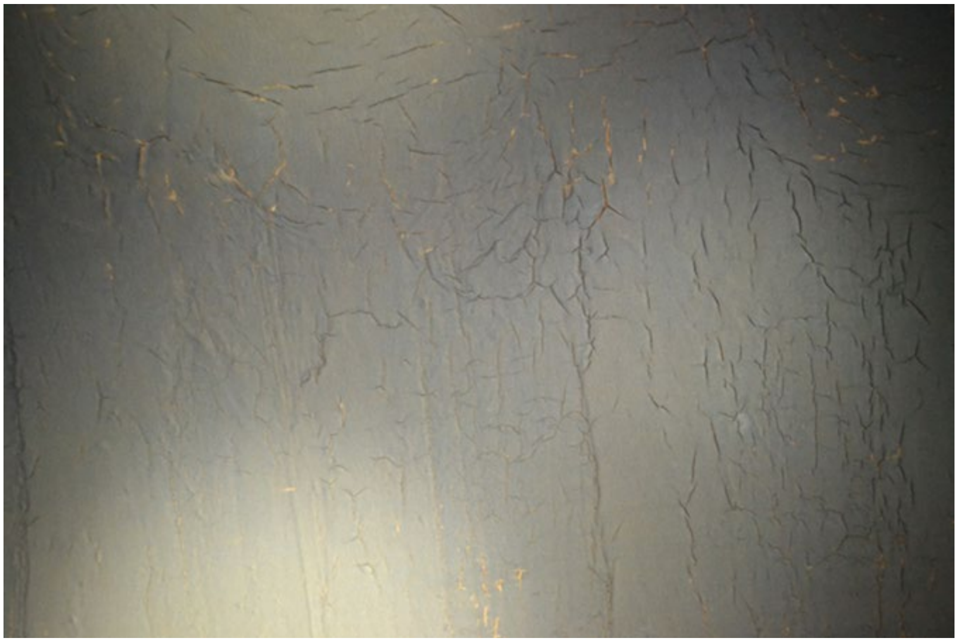


Photo 14. Field representation of stage 3 alligator cracking

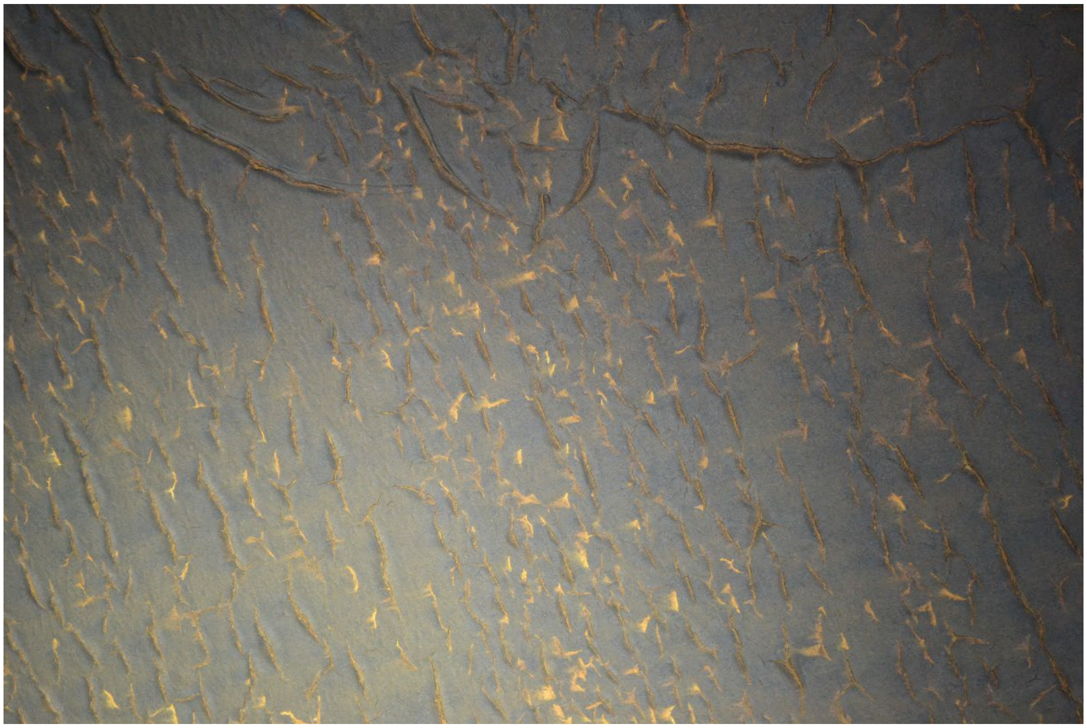


Photo 15. Field representation of stage 4 alligator cracking

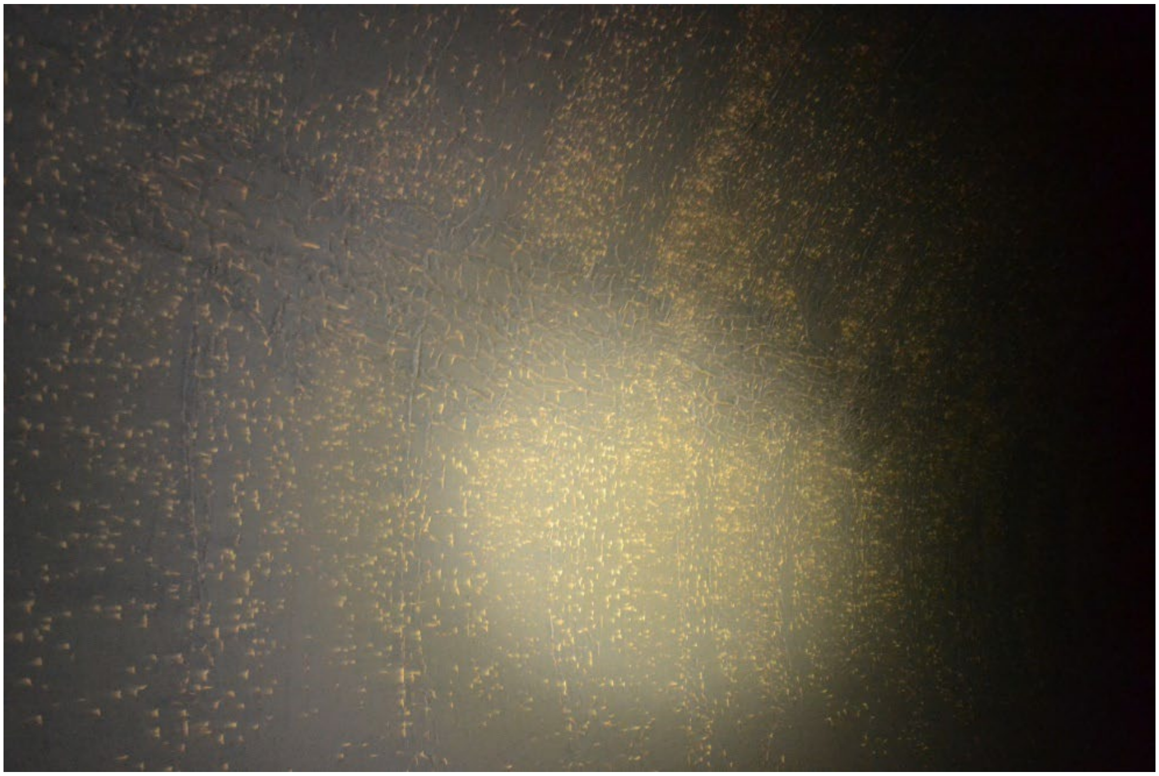


Photo 16. Field representation of stage 5 alligator cracking

Photo 17. Field representation of stage 5 alligator cracking with undercutting

4.3.3 Blisters

Blisters or blistering are dome-like structures where the coating or lining has become delaminated and protrudes from the surface. These can be circular or irregular in shape and filled with water, solvents, gas, or corroded material. Photo 18 and Photo 19 show a gate with a blistered coating.

Photo 18. Blistered coating

Photo 19. Irregular shaped blisters in coating

4.3.4 Cavitation

Cavitation is an erosive force that occurs when water enters areas of low pressure and expands into a vapor; the water vapor enters an area of ambient pressure where it implodes on itself releasing large amounts of energy that can damage the coating or lining and the metal substrate underneath. Photo 20 and Photo 21 show where areas in the lining have completely eroded away due to cavitation thus exposing the steel substrate.

Photo 20. Eroded away lining to steel substrate from cavitation

Photo 21. Close up view of cavitation damaged lining

4.3.5 Chalking

Chalking is the Formation of a white or light-colored powder on the surface of the coating caused by exposure to ultraviolet (UV) light. Chalking typically occurs on exposed exterior coated structures. Photo 22 shows the powder product after wiping a chalked coating surface.

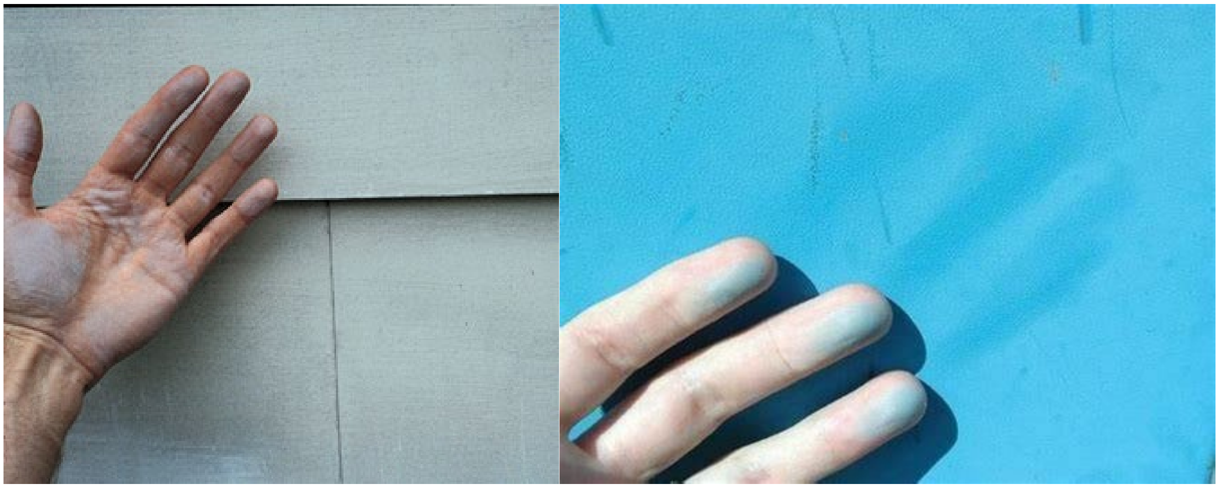


Photo 22. Chalked material that has been wiped off after UV degradation of the coating

4.3.6 Cracking

Cracking is an area where the coating or lining has split. Cracks can go down to the substrate or penetrate through a single coat in a multi-coat system. Photo 23 shows general cracked coatings.

Photo 23. Cracked coating

4.3.7 Delamination

Delamination, also referred to as peeling, flaking, spalling is when the coating or lining has become detached or can be easily removed. This can occur between the substrate and the coating or lining, or between layers for multi-coat systems. It is generally caused by contaminated surfaces or improper application. Photo 24 shows a coating that has peeled from the substrate, Photo 25 shows spalling or missing coating from a trashrack, Photo 26 shows the topcoat that has flaked off, and Photo 27shows a disbonded coating.

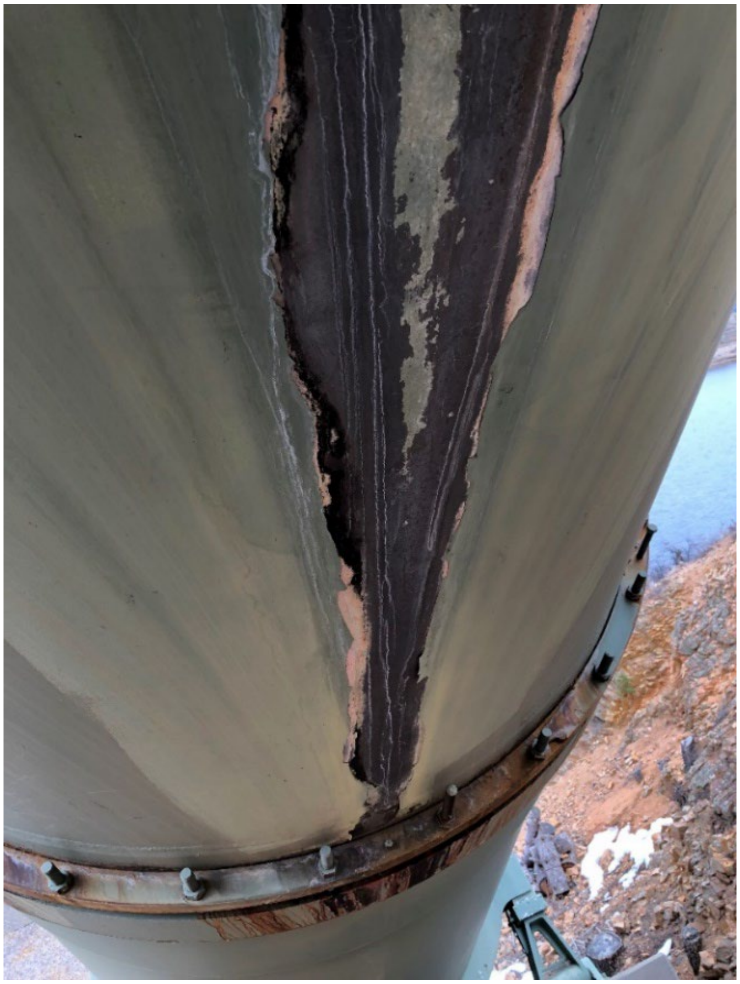


Photo 24. Peeling coating on penstock exterior

Photo 25. Spalling and missing coating of trashrack structure

Photo 26. Flaking topcoat on pipe lining

Photo 27. Disbonded coating on spillway gate

4.3.8 Discoloration

Discoloration is a visible discoloration on the coating or lining surface typically caused staining from by rust and organic matter or by exposure to UV light. This can only be fixed by replacing or applying a new layer of coating or lining. The effect of UV on some coatings is shown in Photo 28.

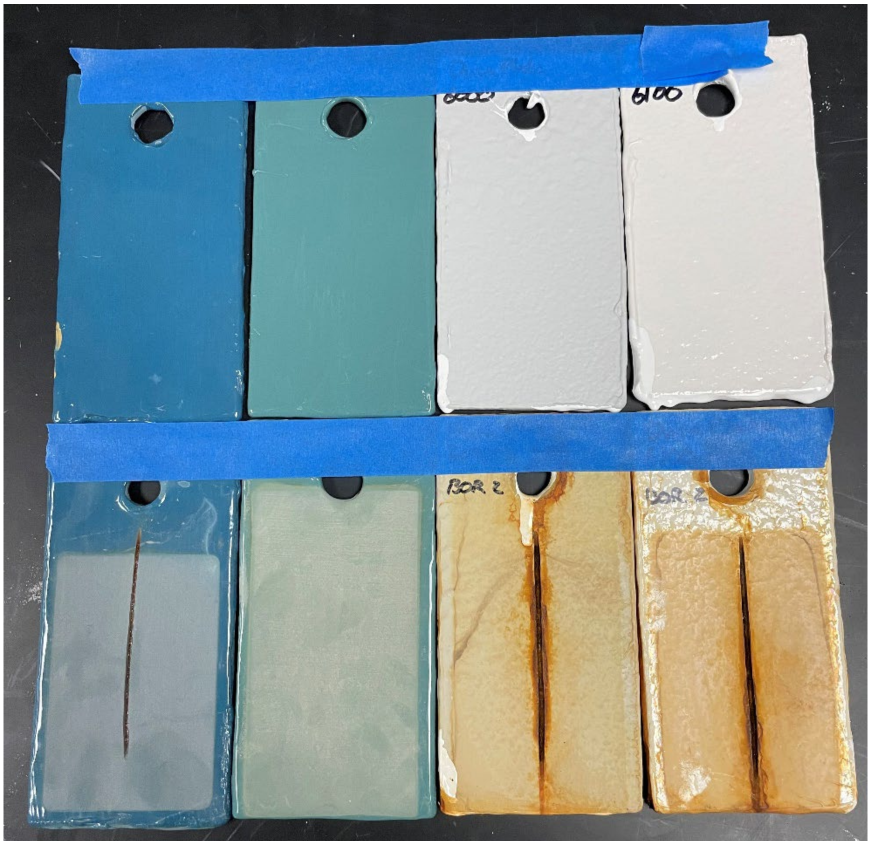


Photo 28. Test panels after 5040 hours of UV exposure

4.3.9 Erosion

Erosion is thin areas of material that have been worn down by flowing water and sediment. Photo 29 shows a lining that has been eroded down to bare metal. The black coating is the topcoat. The grey and red are intermediate coats and the steel substrate is exposed as well. Photo 30 shows results of a laboratory erosion test. The Left disc has a white topcoat and right disc has a grey topcoat.

Photo 29. Eroded coating at a pipe joint

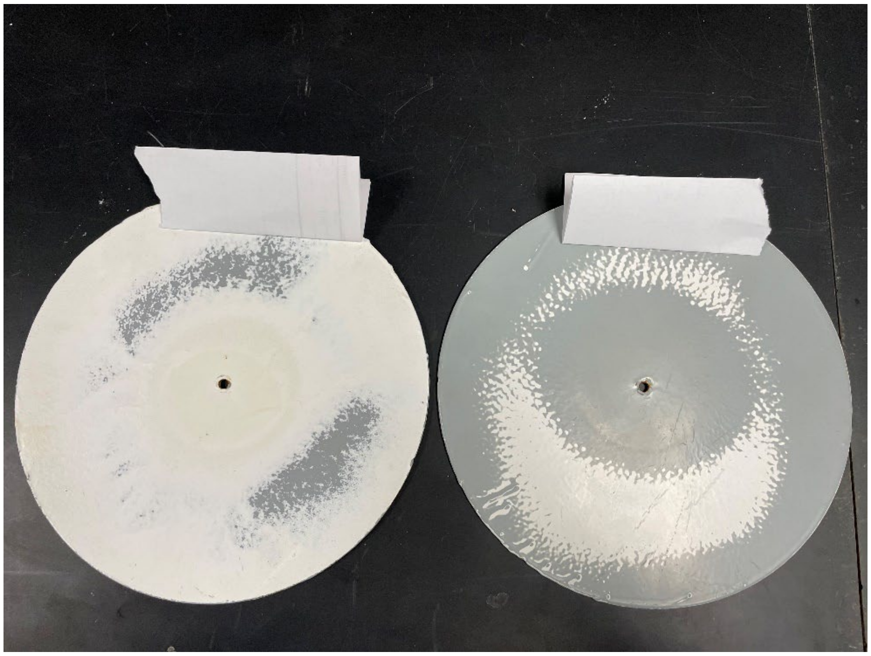


Photo 30. Coatings tested for erosion in laboratory

4.3.10 Pinholes

Pinholes are small defect that go to through the coating to the substrate (Photo 31 through Photo 33). Pinholes can occur during application due to contaminates on the surface or in the material; they can also form during the coating's service life. Pinholes create an area of localized and target corrosion that can result in pitting of the substrate. Pinholes can also lead to the formation of rust nodules which is an accumulation of the corrosion product on the pinhole.

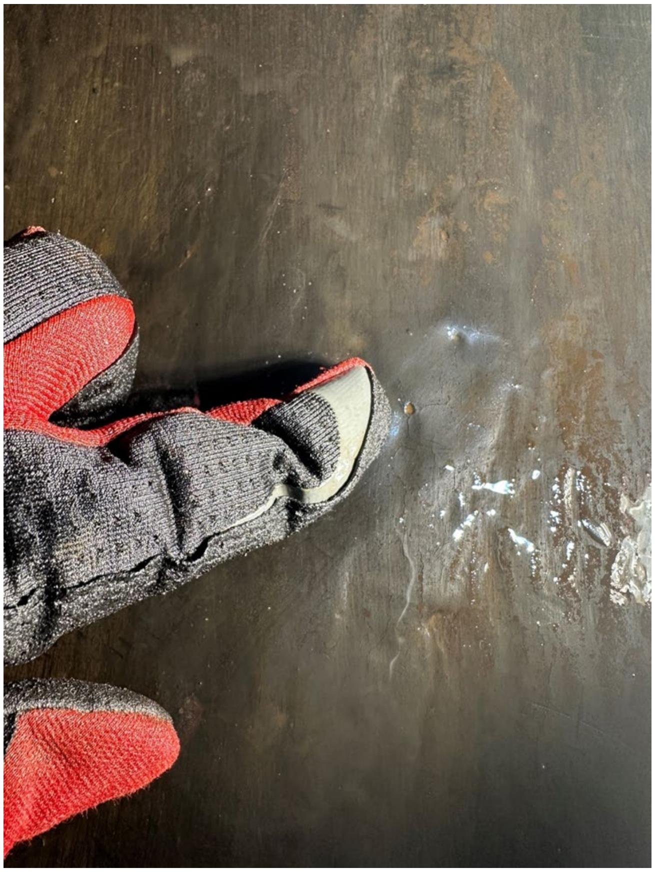


Photo 31. Pinhole in a coal tar enamel penstock lining

Photo 32. Pinholes in vinyl lined scrollcase

Photo 33. Rust nodules on butterfly valve that is heavily corroded

4.3.11 Undercutting

Undercutting occurs in areas of missing or cracked coating or lining. The substrate at the defect area corrodes and the corrosion continues underneath the coating or lining. Photo 17 and Photo 34 show damaged areas to a lining and undercutting has taken place.

Photo 34. Crack that contains undercutting

4.4 Surface Preparation

Surface preparation is typically the most labor-intensive activity in coatings maintenance, taking two-thirds to three-quarters of the time for the entire coating project. Proper surface preparation is essential to achieve adequate adhesion and coating service life. Surface preparation encompasses two descriptors: cleanliness and profile. Contaminants such as grease, oil, or soluble salts could be detrimental to coating longevity and must be addressed during surface preparation processes. Cleanliness refers to the degree in which these contaminants are removed from the surface. Profile, also known as “anchor profile” is a measurement of surface roughness after preparation. Increased roughness provides additional area for coating adhesion. Additionally, it is recommended that sharp edges be eased to provide more surface area. The degree of surface cleanliness and surface profile primarily provides adequate adhesion and coating longevity. Follow the coating manufacturer’s surface preparation requirements at a minimum.

These surface preparation methods are generally considered suitable for spot repairs:

- Abrasive blast cleaning - near white metal blast (SSPC-SP10/ NACE 2)
- Power tool cleaning using a bristle blaster, angle grinder, needle gun, or wire wheel (SSPC-SP11)
- For large spot repairs/ zone repairs, complete removal and recoat would be required following the paint manufacturer’s recommendations for the degree of surface preparation. Typical requirements are abrasive blast cleaning to SSPC-SP10 or SSPC-SP5, near white and white metal blast, respectively.

4.5 Application of Coatings

Coating manufacturers provide detailed instructions for coating applications. These instructions should be followed to provide the longest service life possible for these materials. It is important to understand that your local safety and occupational health staff and TSC coatings professional may have additional safety requirements. You should contact them early to keep your project on schedule.

Factors critical to coating application include:

- The degree of surface cleaning and preparation prior to coating.
- The environmental conditions (e.g., temperature and humidity) during application.
- Application procedure, dry film thickness, number of coats, and coating defects.
- Holiday testing.

Sharp edges, which were hopefully eased, should receive a striping coat which provides an additional coat in an area subject to a potential thin coat.

Non-continuous surfaces such as crevices, riveted construction, back-to-back plates, bolted connections, or skip welds are problem areas and are normally the first areas to experience coating degradation and corrosion. Most coatings available today are highly crosslinked and crack with any movement. Flexible caulking is used to aid in corrosion protection of these features—but this caulking may also require frequent maintenance.

4.6 Coatings in Conjunction with Cathodic Protection

Coatings and cathodic protection (section 5.0) complement each other. Where possible, use them in tandem to achieve the optimal economy and corrosion protection. The coating protects everywhere but at damaged areas and defects. By minimizing the exposed area, coatings significantly reduce the amount of current a cathodic protection system must provide. However, the coating system must be compatible with cathodic protection. Due to high pH produced at defects on a structure, incompatible systems will blister or disbond at defects. Even compatible coatings may disbond when exposed to excessive levels of cathodic polarization. Reclamation TSC Corrosion Specialists should be consulted to properly design cathodic protection systems to protect the structure to prevent cathodic disbondment of coating systems.

4.7 Coating System Maintenance Tasks

4.7.1 Safety

Most original coatings contain hazardous materials, such as asbestos, polychlorinated biphenyls, poly aromatic hydrocarbons found in coal tar products, and the eight heavy metals listed under the Resource Conservation and Recovery Act—arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. When existing coating materials are unknown, test for hazardous materials prior to disturbing. For assistance with hazardous materials and testing, contact a TSC hazardous materials specialist or other qualified professional (e.g., Industrial Hygienist, Safety Staff).

It is a best practice to maintain an inventory of coated surfaces which are known to be hazardous. This inventory should be easily accessible, and the location should be known to all personnel involved in coating system maintenance.

Develop a safety plan before doing any inspection, maintenance, or repair. The many safety hazards in coatings work include exposure to chemicals, flammable materials, confined spaces, and fall protection. Always follow the Reclamation Safety and Health Standards manual, Occupational Safety and Health Administration (OSHA), and Environmental Protection Agency (EPA) regulations. Respirators with air-purifying particulate cartridges may be required when performing inspections, coating applications, or even when cleaning tools. For abrasive blast cleaning, follow the OSHA regulations on using an air-supplied blasting helmet and an appropriate suit. Use proper containment and adequate air flow when working with hazardous materials. Protective suits help prevent clothing contamination and prevent skin contact. Good hygiene should be used to prevent accidental ingestion or inhalation of dust. Solvents should not be used to clean hands upon accidental contact with skin; always use soap and water. Having a well-thought-out plan may save your life.

4.7.2 Condition Assessment

The primary goal of a condition assessment is to obtain information that can be used to plan and budget for O&M activities related to the corrosion protection of a given asset. Assessing the condition of any coating is challenging and subjective.

1. Ensure the safety plan has been developed, reviewed by Safety Staff, and is followed.
2. Begin with a general assessment of the condition of the entire structure. Perform a visual examination using Table 4 and coating defect examples (section 4.3) as guidance to determine the condition of the coatings. Include all coating damage, cracking, blisters, and corrosion spots. It is recommended to include the location, approximate size, and take pictures since outage time constraints might not allow further inspections or immediate repairs. This documentation can also help to provide quantitative information of how fast defects are changing. Appendix B contains a Coating Inspection Log example.
3. Analyze the data to determine the degree of repairs required. Consult corrective action (section 4.7.3). Repair options typically consist of:
    - *No repairs required*
    - *Spot repairs:* Removal of the damaged/degraded coating, surface preparation, and recoat of small damaged areas of the structure.
    - *Zone repairs:* Removal of the damaged/degraded coating, surface preparation, and recoat of large areas of the structure. An example could be a single pipe section, but not the entire pipe.
    - *Overcoating:* Cleaning and surface preparation of the existing coating followed by application of new coatings. This method should not be performed on equipment exposed to immersion conditions. Consult a coatings specialist for suitability and product selection.
    - *Recoat:* Removal of existing coating, surface preparation, and recoat of the entire structure.

4. After the overall condition has been assessed, a project engineer or supervisor can narrow the maintenance options.
5. Determine if the repairs are to be conducted with in-house crews or contracted out.
6. If spot repairs are to be contracted out, conduct a detailed inspection (if not already completed) by a coating specialist to identify damaged coating locations, sizes, and quantities.
7. Evaluate available funds and, if needed, conduct an economic analysis.

Consideration of all these factors ensures a technically and financially sound maintenance decision. A rough estimate of the total percentage of all coating damages (i.e., degradation, visible corrosion, and physical damage). In some instances, the structure can be split into different areas if the condition is severely damaged in one area, but good in another area. This is common when structures are subjected to multiple exposure conditions (for example, above ground penstocks that also have buried or encased sections).

If you have questions or seek additional guidance in determining feasible coating maintenance options or evaluating those options, get help from a Reclamation TSC expert or similar professional.

Table 4. General Inspection Ranking of Coating Conditions

Ranking	Description	Approximate Damage (per 1,000 square feet and as percentage)	Recommended Action
Excellent	Coating is in nearly perfect "as-applied" condition. Coating has limited visible damage.	< 1 square feet (< 0.1%)	None Monitor
Great	Coating has small damaged areas in a few locations. Coating could have some early stages of degradation with surface microcracking but no visible corrosion.	1-5 square feet (0.1-0.5%)	Monitor Spot Repair
Good	Coating has small damaged areas occurring in several localized areas. Coating could have some early stages of degradation with microcracking but no visible corrosion.	6-10 square feet (0.6-1.0%)	Spot Repair
Fair	Coating has small to medium sized damaged areas appearing in several locations or larger damaged areas in a few locations.	11-50 square feet (1.1-5.0%)	Spot/Zone Repair Consider Overcoat (non-submerged)
Poor	Coating has many small to medium sized damaged areas appearing in many locations, larger damaged areas in a several locations, or a single very large damaged area.	51-100 square feet (5.1-10.0%)	Zone repair Overcoat (non-submerged) Consider Recoat
Severe	Coating has extensive small to medium sized damaged areas that appear widespread throughout the inspection area or many large damaged areas	> 100 square feet (> 10.0%)	Recoat
* The approximate damage provides a measure of the average density observed throughout the structure. "Damage" includes defects, breaks, blisters, macrocracking, microcracking, delamination, corrosion, pinholes, etc.			

4.7.3 Corrective Action

After the condition assessment has been completed and evaluated, the coating may be in some state of deterioration, thus requiring corrective action. Corrective action may range from no painting to full removal and recoating. The following sections provide remedial considerations and options based on the inspection assessment.

4.7.3.1 No Repair Required

The inspection assessment indicates the following: (1) the coating is in good to excellent condition, (2) the service environment is mild, (3) little corrosion is expected to progress at coating film breaks, (4) minor discoloration is noted, but appearance is not an important factor, and (5) no significant metal loss is noted. Essentially, this option means "do nothing for "x" number years." It does not mean "do nothing forever." It means that the coating maintenance program is delayed until sometime in the foreseeable future when coating deterioration requires attention or until some time when coating maintenance is scheduled with other major maintenance programs. Another reason for not painting is that funding may not be available for "x" number of years.

4.7.3.2 Spot and Zone Repairs

Spot repairs are in order when the inspection assessment indicates the following: (1) the coating is deteriorating in localized areas, (2) the service environment is mild to corrosive, (3) corrosion is expected to progress at coating film breaks, (4) discoloration is noted, but appearance may or may not be an important factor, and (5) minor metal loss is noted. This option is appropriate for isolated and relatively small areas that do not exceed 1 percent of the total coated surface area and are not in a high appearance area. If color is important, such as in a public area, take color chip samples to the coating manufacturer to match the existing color because the original coating color may have faded. Spot repairs are a viable option for atmospheric, burial, and immersion service exposures. Zone repairs are warranted when the above criteria are met but the damaged areas are larger and/or more widespread. An example zone repair scenario is a section of pipe that is above ground where the coal tar enamel has experienced systematic degradation.

4.7.3.3 Overcoat

Overcoat would consist of possible spot repairs plus full overcoat when the inspection assessment indicates the following: (1) the coating is deteriorating in localized areas that represent between 1 and 3 percent of the total area and are expected to deteriorate further, (2) the service environment is mild to corrosive, (3) corrosion is expected to proceed at coating film breaks, (4) discoloration is noted and appearance is a factor, and (5) minor to moderate metal loss is noted. This option is appropriate for coatings that are in relatively good condition, but defects and corrosion are noticeable. The coating should still be resilient, it can still have a reduced dry film thickness, but adhesion should be good where the coating has not deteriorated. When overcoating an existing paint, a test patch should be applied to determine compatibility between the coating materials. The test patches should be evaluated between 1 and 3 months after application. The structure's appearance may be of aesthetic importance (such as when in public view), and a full overcoat will provide a uniform color and gloss. This is a viable option for coating structures in atmospheric service exposures, but it is not recommended for burial and immersion service exposures.

4.7.3.4 Recoat

Completely removing the old coating and recoating is in order when the inspection assessment indicates the following: (1) the coating is deteriorating in localized and large areas representing greater than 3 percent of the total area, and it is expected to deteriorate further; (2) the service environment is mild to corrosive; (3) corrosion is expected to progress at coating film breaks; (4) discoloration is noted and may or may not be an appearance factor; and (5) moderate to significant metal loss is noted. This option is conducive to coatings that are in poor condition and are no longer protecting the substrate. This option requires full removal of all the existing coating material and recoating the entire surface. This is a viable option for atmospheric and immersion service exposures.

5.0 Cathodic Protection

Cathodic protection uses direct current to mitigate metal corrosion in an electrolyte, i.e., in burial or water immersion. Figure 1 showed how anode and cathode sites form localized corrosion cells. The difference in potential between these sites is the driving potential for corrosion. Cathodic protection protects the entire surface of a metal structure by making it a cathode of a galvanic or electrolytic cell through a process called polarization. Through polarization, the driving potential in each localized corrosion cell is reduced or eliminated. The passage of current then causes the electrolyte surrounding a protected structure to become more basic or alkaline (high in pH). This protective current may come from:

- A more active metal such as zinc or magnesium.
- An external source of power such as a rectifier.

The use of cathodic protection is a safety and economic consideration. Cathodic protection, usually in conjunction with protective coatings, can allow a long service life equivalent to that obtained from using more expensive alloys. Note that cathodic protection is typically not an effective solution for corrosion mitigation in locations such as the interior surface of a siphon or other pipeline due to the high flowrates; however, it may be helpful during stagnant periods when the pipelines are not flowing but have not been dewatered. Evaluating the need for cathodic protection on structures should be performed on a case-by-case basis.

5.1 Cathodic Protection Equipment

The basic equipment needed for cathodic protection work includes:

- Galvanic anodes or impressed current anodes and a rectifier.
- Junction boxes where multiple anodes may come together.
- Test stations for electronic access to cathodically protected structures for performing measurements.
- Shunt resistors used for measuring anode current by application of Ohm’s Law.
- Variable resistors used to adjust anode current throughout.
- A high-impedance (10 MΩ minimum) portable voltmeter.
- A reference cell – usually a copper/copper sulfate electrode (CSE).
- Wire cables.

This document will explain proper use of this equipment to accomplish common cathodic protection tasks.

5.2 Cathodic Protection Criteria

The Association for Materials Protection and Performance (AMPP) (formerly SSPC and NACE International) is recognized worldwide as a premier professional society and standards setting organization concerned with corrosion control. AMPP has a number of industry standards dealing with cathodic protection, including legacy standards from NACE. The most current standards are always used in industry practice. These standards generally include three main criteria for protection of ferrous metal to ensure effective cathodic protection, especially when the protected structure cannot be observed:

1) A polarized potential equal to or more negative than -0.850V with respect to a standard saturated copper/copper sulfate reference cell.
2) 0.100V of polarization more negative than the native potential of the protected structure.
3) A polarized potential no more negative than -1.000V with respect to a standard saturated copper/copper sulfate reference cell for all steel reinforced concrete or mortar coated steel pipes.

These criteria were derived semi-empirically and have served the industry well for many years. Note that these criteria involve determining polarized electrochemical potential with extraneous voltage drop errors eliminated. Special instances may require adjustments to the usual criteria. For instance, locations with high sulfates calls for a minimum -0.950V(CSE) polarized potential criterion instead of the usual -0.850V(CSE). Excessive polarization may cause either hydrogen embrittlement or high pH corrosion of some metals.

Reclamation primarily uses the first criterion. The second is typically used when structures are poorly coated and protecting them to the first criterion is not economically justifiable. The third is used for ferrous structures embedded in concrete. Additionally, Reclamation generally limits polarized potentials on coated steel structures to a value no more negative than -1.100V(CSE) to prevent possible damage to coatings.

5.3 Cathodic Protection Systems

Cathodic Protection is achieved by various means and depends on equipment and site conditions. Below describes the different style of systems.

5.3.1 Galvanic Anode Cathodic Protection Systems

As described previously, oxidizers such as oxygen in an electrolyte rob a metal of electrons causing corrosion. A galvanic series shows that some metals are active and readily give up electrons while others are noble and hold on to them. If two such metals are electrically connected and in a corrosive electrolyte, the more active metal will tend to provide the electrons demanded by oxidizers about its surface, as well as those about the surface of the more noble metal. Since the more noble metal does not need to supply all those electrons, it does not corrode as rapidly. This is the principle for galvanic cathodic protection (GACP), which may also be known as sacrificial anode cathodic protection. Corrosion still takes place; one metal is simply "sacrificed" for another that is more valued. Figure 3 shows a typical installation with a pipe being protected by a magnesium anode. All the cables, including a test cable, are terminated in a test station.

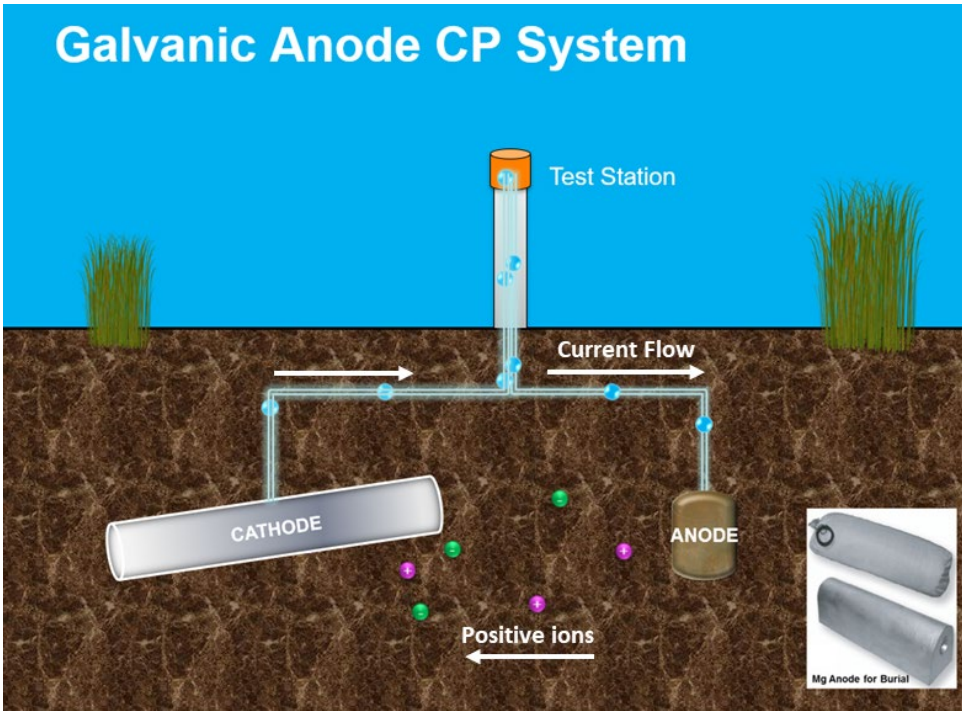


Figure 3. Typical galvanic anode cathodic protection system installation

Table 2 shows that magnesium, zinc, and aluminum are high on the list as anodic metals and are significantly separated from iron and steel in the galvanic series. As expected, these anodic metals are commonly used to protect iron and steel. However, aluminum anodes are only used in high-chloride environments; aluminum and its alloys tend to passivate in the absence of chlorides.

Only galvanic anode material specifically alloyed for that use must be used for cathodic protection. ASTM B843 *(Standard Specification for Magnesium Alloy Anodes for Cathodic Protection)* lists three groups of magnesium alloys—AZ63, AZ31, and M1. The M1 alloy is a high-potential material that is about 200 mV more electronegative than other magnesium anode alloys. Therefore, while the standard potential magnesium anode has an open circuit potential of about -1.5 V(CSE), that of the higher potential magnesium anode is about -1.7 V(CSE). Either alloy is suitable for use in soil and fresh water.

ASTM B418 *(Standard Specification for Cast and Wrought Galvanic Zinc Anodes)* lists two types of zinc anodes—Type I and Type II—Type I, along with a Mil Spec. A Type I anode is intended for use in seawater and brackish water at temperatures less than 50 °C. Type II and high-purity zinc anode are intended for soil and fresh water. Zinc anodes have an open circuit potential of about -1.100 V(CSE).

Aluminum anodes are available in a Type I for open seawater and Type II for seawater/mud applications. Because of the high saline environments required when using aluminum and their rarity within Reclamation, nothing further will be mentioned here regarding aluminum anodes.

Sacrificial anodes provide a relatively small driving voltage when connected to steel (see Table 2) and subsequently generate relatively small amounts of current. Sacrificial anode systems are generally used with a combination of:

- Low-resistivity environments.
- Small surface areas of metal to be protected.

Typical magnesium and zinc galvanic anodes are shown in Photo 35.

Photo 35. Typical magnesium and zinc galvanic anodes

Galvanic anodes may be purchased in bare or packaged (i.e., bagged) form depending on the application. Bagged anodes are used in burial applications while bare anodes are used for immersion. A dielectric shielding material, such as a plastisol coating on the bottom and sides of the direct mount anode, can provide the necessary shielding to prevent over polarization of the structures surface around the anode.

5.3.2 Impressed Current Cathodic Protection Systems

5.3.2.1 General Description

External power sources can also deliver cathodic protection dc current to a structure. This is referred to as Impressed Current Cathodic Protection (ICCP). Figure 4 shows a typical ICCP system installation with a rectifier passing current through a set of anodes to protect a buried pipe; note the test station.

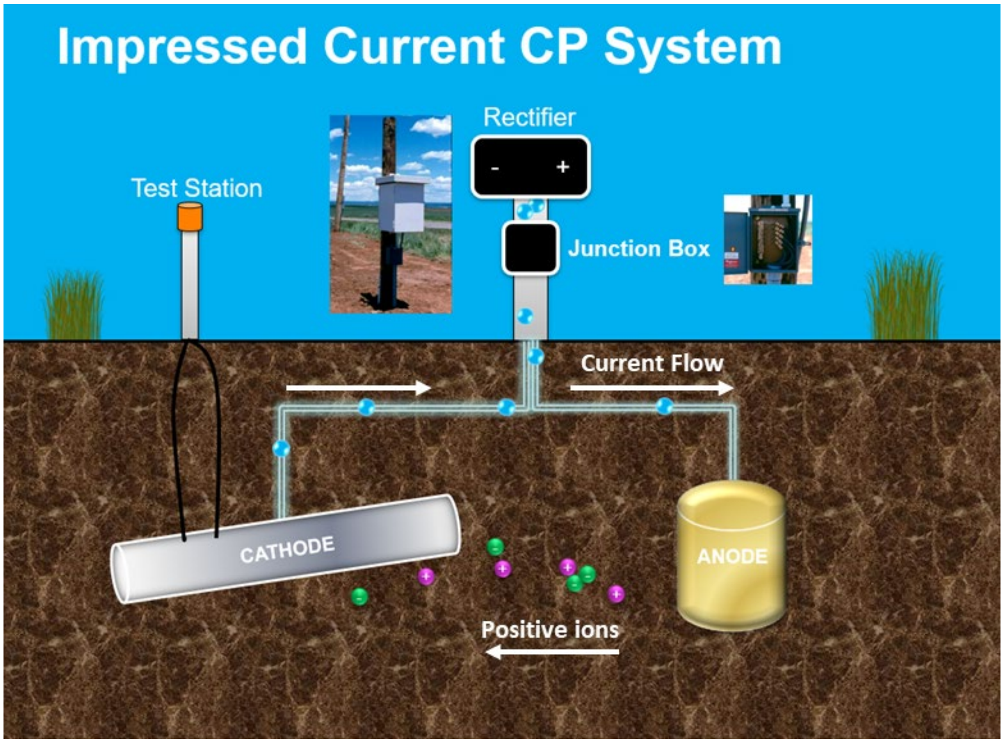


Figure 4. Typical ICCP system installation

ICCP systems usually introduce current into the electrolyte through anodes made of corrosion-resistant material such as graphite, high-silicon cast iron, platinized titanium or niobium, or mixed metal oxide (MMO) on titanium or niobium. Some typical anodes are shown below in Photo 36.

Photo 36. Typical ICCP anodes. MMO flush mounted disk anode (top), polymer sausage anode (bottom left), and MMO wire anode (bottom right)

Impressed current systems have several advantages. Because they can induce much greater driving voltages, they can supply much more current than galvanic anodes. As a result, ICCP systems can protect structures with large, exposed metal surface areas. They can also protect structures in higher-resistance environments, where sacrificial anodes produce too low a voltage to be effective. The cost per ampere is less for impressed current systems than for galvanic anode systems.

However, impressed current systems also have disadvantages. The typical ICCP rectifier operates on 115V ac or greater input power. This can present personnel safety concerns not relevant with low-power galvanic anode systems. Poorly designed or adjusted systems can generate too much power from an ICCP system which can potentially damage the coating on a structure, a phenomenon called "cathodic disbondment." Too much current can also produce enough hydrogen at a structure to cause hydrogen embrittlement of some metals. This is usually an issue with high-strength steels and certain alloys. Furthermore, while not commonly observed, misconnecting the positive and negative sides of an ICCP system can make the structure the anode and result in highly accelerated corrosion of that structure. This is not possible with galvanic anode systems. Impressed current systems have more parts that can break down and generally require more maintenance and upkeep than galvanic systems. They can be accidentally turned off and may be susceptible to lightning strikes and power outages.

The most common dc current source for ICCP is a rectifier. However, if electrical power is not available, other dc power sources are available. One of the other potential sources of dc current are solar power supplies. Reclamation rarely uses devices other than rectifiers.

5.3.2.2 Rectifiers

The typical rectifier has two basic components. The first component is a transformer to control the driving voltage. The second component is a rectification section, most commonly a diode bridge, to convert the ac input current to dc output current. In addition, there are gauges, connectors, fuses, taps to adjust the secondary output on the transformer, and other accessories to make the system safe and workable. Photo 37 shows a typical rectifier cabinet as it might appear in the field. Photo 38 shows a typical board inside the cabinet.

Photo 37. Typical rectifier cabinet

Photo 38. Typical rectifier board inside a cabinet

The most often used rectifier within Reclamation is a simple air-cooled, single-phase ac input rectifier with full-wave dc output. However, rectifiers are available in a variety of configurations, such as:

- Three-phase rectifiers to meet large power requirements (these are usually economical when the power required exceed 2000 watts).
- Silicon-controlled rectifiers.
- Rectifiers with selenium stack rectification sections (these are usually older units).

The typical Reclamation rectifier is usually set up to provide a constant dc voltage output. However, rectifiers may also be ordered from a supplier to provide a constant dc current output. Some rectifiers are also made to monitor the potential of a structure and automatically adjust the dc voltage output to achieve a set potential; these are known as potential-controlled rectifiers. Consult an electrician and personnel with considerable cathodic protection experience when installing a new or replacement rectifier or when repairing a rectifier.

5.3.2.3 Impressed Current System Installation

The installation of an ICCP system follows many of the same principles as those for a sacrificial system. A significant difference is that a dc current source is installed between the structure and the anode bed. An ICCP system also uses different anode materials. The anode bed is usually a remote type; but ICCP systems may use a distributed anode arrangement in some instances. Multiple anode cables connect to a common header in an above-ground junction box. Here each anode cable connects to a shunt resistor to permit current flow measurement. From the junction box, usually below the rectifier, a common anode cable travels to the positive (+) terminal of the rectifier. The structure cable connects to the negative (-) terminal of the rectifier.

Most constant voltage rectifiers have exposed taps on the secondary side of the transformer. Taps allow the output voltage to be increased or decreased in increments. Some rectifiers have knobs that allow varying the voltage continuously anywhere within the operating range. The ability to adjust the voltage provides the necessary current for adequate cathodic protection without exceeding prescribed electrochemical potential limits. In setting this voltage, one normally starts at the lowest setting, increasing it in small steps. The impact on structure potential is measured in between increases until the desired effect is achieved.

5.4 Cathodic Protection System Maintenance and Testing

5.4.1 General

Cathodic protection systems require periodic attention to ensure that they function properly. Some checks only require visual observations. Others require a portable high-impedance voltmeter, cables in good condition, and a calibrated reference electrode cell (usually a copper/copper sulfate reference cell). Regularly scheduled inspections, good record keeping, and acting on the recommendations of the qualified cathodic protection professional can head off problems. Adjustments should not be made unless approved by a cathodic protection professional.

The following will describe common requirements for maintaining cathodic protection systems. This guidance along with system design requirements shall be used to develop cathodic protection system specific standard operating procedures and documentation forms.

5.4.2 Buried vs. Immersed Structures

Cathodic protection systems may be installed on buried or immersed structures. Buried structures are always in contact with their electrolyte; immersed structures may be dewatered at times. Since a cathodic protection system will not operate without the electrolyte, the testing procedures described below must be performed during times when an electrolyte is present. If a structure is to be dewatered, turn off an ICCP system rectifier, and turn it back on when the structure is re-immersed.

Readings may not be reliable on structures until the cathodic protection systems have been energized for a minimum of two weeks. Some structures take longer than others to fully polarize and the cathodic protection systems to stabilize. This should be accounted for on structures such as pump columns, trashracks, and other immersed structures where the structure has been dewatered for any period.

Potential readings on buried structures consists of individual measurements taken directly over the structure at the test stations. However, on structures such as pipelines, occasional (e.g., 10 years) close interval surveys allow assessment of cathodic protection effectiveness between the usual test points and are a good procedure for locating and addressing trouble spots or inadequately protected locations on a structure before problems develop.

5.4.3 Safety

Safety is an essential part of cathodic protection system maintenance. Identifying and understanding hazards involved with working on or near cathodic protection systems is essential to creating a safe working condition. All maintenance activities must be conducted in accordance with FIST Volume

1-1, Hazardous Energy Control Program, FIST Volume 5-14, Electrical Safety Program, and the Reclamation Safety and Health Standards. A job hazard analysis must be conducted as well.

Electrical hazards can be present with cathodic protection systems. ICCP systems present more electrical safety concerns than GACP. This is due to the higher dc voltages involved in ICCP systems than those observed with GACP systems. Most Reclamation rectifiers are single-phase 115 V ac input voltage; some could be 3-phase and higher voltage. Personnel must understand the equipment when working with cathodic protection systems. It is a good practice for maintenance personnel to not assume equipment remains properly grounded, but to verify it is not energized before taking hold of it. A small handheld ac voltage detector is useful for this purpose.

Rectifiers, junction boxes, and similar components are normally kept padlocked to prevent unauthorized access and tampering.

Insects such as wasps and spiders present a common safety concern for any system. Insects and vermin have been known to occupy rectifier cabinets, junction boxes, and sometimes test stations. It is important to anticipate these and not be surprised by them, as shown in Photo 39. Ensuring that equipment is screened and that there are no unused or unsealed openings will minimize this issue.

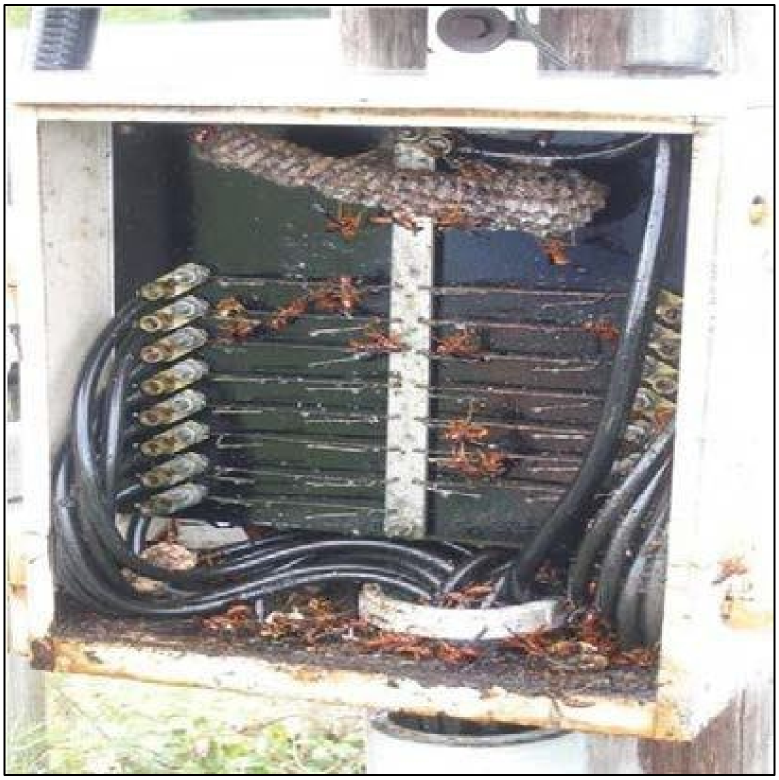


Photo 39. Wasps occupying a junction box

Note the failure to properly connect the conduit at the bottom, providing easy access for the wasps.

5.4.4 Personnel

Maintenance and testing of impressed current systems require a higher level of appreciation for electrical and electronic components and associated hazards. Only trained personnel are to perform the required maintenance and testing on cathodic protection systems. Training can be obtained through TSC and/or AMPP.

5.4.5 Equipment Used for Testing

5.4.5.1 Voltmeter

The voltmeter used for testing must have high input impedance of 10 MΩ or greater. The cables must be in good condition with no nicks in the insulation. A lead with damaged insulation in contact with the electrolyte can cause false readings. Since most readings involve dc voltage, the setting on a multi-function meter must be adjusted accordingly.

5.4.5.2 Reference Electrode or Cell

Reference cells for fieldwork typically consist of a metal surrounded by a standard solution in a plastic tube that has a porous plug at the end. Though they are quite stable, care must be taken not to contaminate them and to control their temperature, or to compensate for variations in reference cell temperature. A copper/copper sulfate reference cell is commonly used for soil or freshwater testing. When brackish water is involved, a silver/silver chloride reference cell may be employed instead. In addition, zinc can also be used as a permanent, in-place, reference electrode either bare for submerged applications or in a chemical backfill for buried use.

A CSE provides the baseline for most electrochemical potential measurements in soil or fresh water. Make sure to connect the structure to the positive terminal of a typical digital voltmeter and the reference cell to the negative terminal, in order to obtain the proper polarity. Place the tip of the reference cell on the soil or in water near the structure of interest when taking readings. It may be necessary to wet the soil prior to placing the reference electrode to reduce the contact resistance of the measurement. Reference cells, replacement components, and copper sulfate are available from any cathodic protection supply company. Photo 40 shows a typical reference cell and its components.

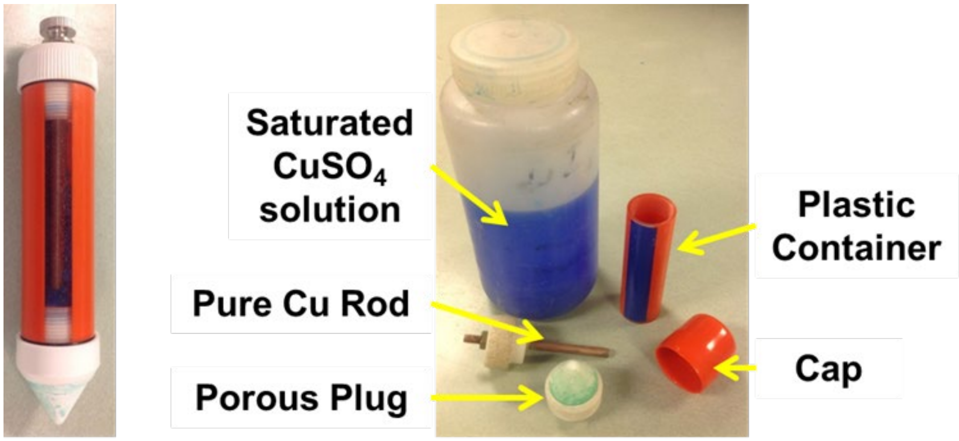


Photo 40. Copper/copper sulfate reference cell and components

CSEs or copper sulfate reference cells are more stable than some other reference electrodes and rugged for field use. However:

- If the solution becomes contaminated, especially by chlorides, the CSE will not provide accurate readings. Check the calibration regularly (see 5.4.5.3).
- A CSE provides a correct baseline at a cell temperature of 77 ºF (25 ºC). Temperature conversions will need to be performed for temperatures outside 77ºF (25 ºC).
- Sunlight or other ultraviolet (UV) shining through a clear tube has been shown to affect the readings, so it is best to place opaque tape over areas of clear tube when taking readings. Keep the reference cell out of direct sunlight when not in use.
- If the solution becomes cloudy, clean the reference cell, replace the solution, and recalibrate.

5.4.5.3 Reference Cell Calibration

Testers must ensure that reference cells are properly calibrated as follows before setting out to take readings:

1) Obtain at least two cells, preferably three.
2) Obtain distilled or deionized water and reagent-grade copper sulfate crystals.
3) Disassemble the cells and drain any remaining copper sulfate solution and crystals, and properly dispose.
4) Rinse the reference cell components to ensure they are clean. Do three final rinses with distilled water.
5) Using inert grit paper (**do not** use steel wool or grit paper contaminated by foreign metals), abrade the surface of the copper rods from the centers of the cells to obtain a bright surface; the surface may still show evidence of pitting. When completed, rinse the rods with distilled water.
6) Reassemble the cells, placing reagent-grade copper sulfate crystals in the bottom and filling them with distilled water, or (preferably) pre-saturated copper sulfate solution. Ensure that the copper sulfate has formed a saturated solution before proceeding; there must always be excess copper sulfate crystals in the bottom of a reference cell tube to ensure saturation.
7) The assembled reference cells must be allowed to reach room temperature. If there is a clear window on the reference cells, cover with opaque electrical tape or the like to prevent UV effects.
8) Immerse the tips of the reference cells in a container of water and take a dc voltage reading between sets of cells with a high-impedance voltmeter. If two cells are employed, the voltage difference between them must be no more than 5 mV. If this range is not achieved, repeat steps 3 through 8 until a 5-mV difference or less is achieved. If three cells are employed and one is outside the 5-mV range, eliminate this one and proceed.
9) Of the two reference cells within the 5-mV range, set one aside as a reference standard and use the other in the field. Check the field cell against the reference standard at least at the end of each work period (e.g., a shift) to ensure that the field reference is not drifting excessively due to contamination, temperature extremes, etc. Keep the porous cell tips from plugging with salt deposits by placing a little bit of water in the protective end caps, or by keeping the tips in a container of water.

5.4.5.4 Test Stations and Junction Boxes

Test stations, as shown in Photo 41, provide above-ground electrical contact for testing an inaccessible structure. With galvanic anode systems, they may also serve as the connection points between anodes and the structure. In such situations, the test station will contain shunts (calibrated resistors) to allow measurement of the current using Ohm's Law. Test stations may contain variable resistors to reduce the current drawn from an anode, limiting the current to only the amount necessary to maintain adequate protection.

Test stations for galvanic anodes contain a minimum of three cables, two cables from the structure and one cable from each anode. One structure cable, usually a #12 AWG cable with high molecular weight polyethylene (HMWPE) insulation, provides a test connection while the other #12 AWG structure cable is connected to the anodes through individual anode shunts. In such situations, the test station will contain shunt resistors to allow measurement of current by application of Ohm's Law and may contain variable resistors to reduce the current drawn from an anode, limiting the current to only that necessary to maintain proper protection.

For test stations used exclusively for testing, Reclamation normally requires at least two cables from a structure. One cable, usually a #12 AWG stranded cable with HMWPE insulation, provides a test connection while the other #12 AWG stranded cable with HMWPE insulation permits hot spot protection should it be required in the future. Test stations at electrical isolation joints typically have two sets of such cables, with one set extending from each side of the isolation joint. Test stations at intersections with foreign pipes or other structures, such as casings, may have two cables from the foreign structure, two cables from the Reclamation structure, and a connection from an in-place reference cell between the Reclamation structure and the foreign structure. Connections to a foreign structure must be permitted by the owner of that structure.

Through a test station, an examiner can gain information as to whether the cathodic protection system is working properly, whether the anodes have been consumed, etc. The cables should be continuous and without splices.

Photo 41. Typical test station with board exposed

When a cathodic protection system employs more than two or three anodes, the recommended procedure is to bring the cables from these together in an above-ground junction box. Junction boxes can serve a function similar to test stations, but they provide much more room. They typically contain a phenolic panel with an attached busbar. Anode cables pass through a conduit connected to the junction box. The cables can then connect to resistance shunts and often variable resistors that then connect to the busbar. A single lead from the structure (in the case of a galvanic anode system) or from the positive side of the rectifier (in the case of an impressed current system) connects to the busbar. If the junction box is to serve as a test station, a separate test lead from the protected structure will also be connected to the board for testing. If multiple structures are collectively protected by one cathodic protection system, their cables may similarly join to a common header in junction box.

Cables and cable connections must always be labeled, at least in boxes where multiple cables are involved. Use printed factory-supplied labels and apply a clear shrink sleeve over the cables. A typical junction box is shown in Photo 42. Junction boxes should have vents which are screened to prevent the ingress of insects or rodents. Junction boxes must meet National Electrical Manufacturers Association 3R requirements as a minimum.

Photo 42. Typical junction box

5.4.6 Galvanic Anode Systems Maintenance

To ensure that the cathodic protection system is functioning correctly, personnel must examine system components and electrolyte conditions on a routine basis. The following procedures must therefore be followed for GACP systems.

5.4.6.1 Test Stations and Junction Boxes

[Inspect test stations and/or junction boxes for damage.] Check for damage and/or vandalism to above-ground junction boxes and test stations where anodes join the structure cable. Look for gross visual damage to buried cables from excavations or farm equipment, etc. If damage occurs often consider barriers and changes in design that may help minimize this occurrence.

[Verify connections and clean out any debris.] Inspect the enclosure for general cleanliness and clean any dirt and debris. Ensure enclosure seals, vents, conduit connections, and conduit are not damaged. Inspect insulating members for cleanliness, damage, and signs of overheating. Check all wiring connections are tight. Inspect for signs of corrosion and clean if present. Visually observe wires and insulation for damage such as broken strands, nicks, or signs of overheating.

5.4.6.2 Potential Readings

[Measure and record electrochemical potential readings of the protected structures.] To measure and record electrochemical potential readings:

1) Obtain a portable high-impedance voltmeter (see 5.4.5.1). Set the voltmeter to dc "volts" for structure potential readings.
2) Obtain a calibrated copper/copper sulfate reference cell (see 5.4.5.2 and 5.4.5.3).
3) Connect the structure (i.e., accessed through the test station test lead) to the positive terminal of the typical digital voltmeter for the correct polarity in measurements. Connect the negative voltmeter terminal to the CSE.
4) Press the ceramic plug of the CSE into the soil or immerse in the water above or near the structure. It is desirable and sometimes essential to wet the soil before applying the CSE to reduce contact resistance.
5) Since currents in the electrolyte can cause voltage drop errors called IR drop, galvanic anode connections to the structure need to be momentarily interrupted while taking readings. However, interrupting cathodic protection current for more than a few seconds at a time could result in some depolarization of the structure and readings that are somewhat in error. A current interrupter may be useful when taking these readings, but potentials on sacrificial anode systems are often taken while manually interrupting the current. Any other currents flowing through the soil in the area of a reading must also be interrupted while taking potential readings. This could include such locations as cathodically protected foreign structures crossing the pipe being tested (requires coordination with foreign structure owner).
6) Take electrochemical potential readings with current flowing and with current interrupted (instant-OFF). When measuring the "instant-OFF" potential (polarized potential) on the voltmeter, it is standard to record the second value shown on the meter after interrupting the current. Record the sign, the numerical value of the potential, and the type of reference electrode used (e.g., -0.920 V(CSE)).

Prepared data sheet, Galvanic Anode Test Station Readings (POM-502) is available for documentation.

5.4.6.3 Anode Current

[Measure and record the current flowing through each anode on the data sheets.] This also requires a portable high-impedance voltmeter, normally set to take dc millivolt readings. These readings are taken with current flowing by measuring the voltage across the anode shunt resistor connection tabs and employing Ohm's Law to calculate the current. For instance, if 6 millivolts (0.006 V) is measured across a 10-milliohm (0.010 Ω) resistor, then the amperage flow is:

$$\frac{0.006\,V}{0.010\,\Omega} = 0.6\,A$$

The tester records the actual millivolt reading, the resistance value of the resistor, and the current obtained after the application of Ohm's Law.

5.4.6.4 Submit Records for Review

[Submit records for review.] The site must maintain a record of inspections, along with recommendations and actions taken in an accessible form such as CARMA. Good records can show trends before a problem develops.

Have the data sheets from the inspections reviewed by a qualified cathodic protection professional. Provide the reviewer with the current and previous inspection results.

5.4.6.5 Repairs and Adjustments

The reviewer may recommend adjustments to the cathodic protection system. These adjustments may be needed since soil conditions may change somewhat over time, anodes may be consumed, and the condition of the structure coating may change. The system must maintain the protection criteria described in the specific equipment SOP and generally described in this publication (see 5.2).

5.4.7 Impressed Current System Maintenance

To ensure that the cathodic protection system is functioning correctly, personnel must examine system components and electrolyte conditions on a routine basis. The following procedures must therefore be followed for ICCP systems.

5.4.7.1 Test Stations and Junction Boxes

[Inspect test stations and/or junction boxes for damage]. Check for damage and/or vandalism to above-ground junction boxes and test stations where anodes join the structure cable. Look for gross visual damage to buried cables from excavations or farm equipment, etc. If damage occurs often consider barriers and changes in design that may help minimize this occurrence.

[Verify connections and clean out any debris.] Inspect the enclosure for general cleanliness and clean any dirt and debris. Ensure enclosure seals, vents, conduit connections, and conduit are not damaged. Inspect insulating members for cleanliness, damage, and signs of overheating. Check all wiring connections are tight. Inspect for signs of corrosion and clean if present. Visually observe wires and insulation for damage such as broken strands, nicks, or signs of overheating.

5.4.7.2 Rectifiers

[Inspect rectifier cabinet for damage.] Check for damage and/or vandalism to rectifier cabinet. Look for gross visual damage to buried conduit and cables from excavations or farm equipment, etc. If damage occurs often consider barriers and changes in design that may help minimize this occurrence.

[Verify the rectifier is energized and set in accordance with equipment SOP.] Checks therefore include:

1) Verifying the rectifier tap settings are in the positions recorded on the last inspection sheet. If the setting is not in the expected position, investigate the cause and correct if necessary.
2) Verifying that there is dc voltage and current output. Confirming that there is voltage across the rectifier current shunt (see 5.4.6.3), that the current gauge on the panel indicates current flow (be certain the gauge is not frozen in place), will accomplish this. Ideally, dc voltage and current output should be measured and compared to prior findings.*

> *Note: DC voltage and amperage gauges on the panel are usually not very accurate and sometimes fail. A gauge that indicates current flow may simply have failed in that position and may not be indicating actual current flow. These gauges tend to last longer if there is a switch to take them out of the circuit when not needed and if this switch is left in the "off" position following readings. This switch can sometimes be used to determine if the gauge is frozen in place. A portable voltmeter is more reliable. A voltage reading across the dc output terminals with a portable voltmeter is informative but will not indicate if current is flowing. A rectifier can hold a voltage across its terminals even when one or both cables are broken, and no dc current is flowing.

[Verify connections and clean out any debris.] Inspect the enclosure for general cleanliness and clean any dirt and debris. Ensure enclosure seals, vents, conduit connections, and conduit are not damaged. Inspect insulating members for cleanliness, damage, and signs of overheating. Check all wiring connections are tight. Inspect for signs of corrosion and clean if present. Visually observe wires and insulation for damage such as broken strands, nicks, or signs of overheating.

While the rectifier is on, perform these actions:
[Record rectifier tap settings and dc measurements.]

1) Record the coarse and fine tap settings. If the rectifier has a variable knob, record the knob setting.
2) Record the dc voltage and current from the gauges on the rectifier panel. If these gauges are supplied with an on/off switch, turn them on to take readings and off again when done; this will help ensure their reliability when needed.

[Measure and record dc readings.]

1) Measure and record the voltage across the rectifier dc output connections with a portable voltmeter.
2) Measure and record the voltage across the rectifier shunt connections with a portable voltmeter and convert to amperage. Rectifier shunts are normally rated in A/mV; therefore, multiply the shunt rating by the millivolts read to obtain the total rectifier dc amperage output. For instance, with a 10A/50 mV rectifier shunt, a millivolt reading of 10 mV across the shunt would mean that the rectifier is passing 2A.

Prepared data sheet, Voltage Controlled Rectifier Data Sheet (POM-500) is available for documentation.

5.4.7.3 Potential Readings

[Record electrochemical potential readings of the protected structures.] (See 5.4.6.2). Install a current interrupter in the dc output circuit of the rectifier. Potential readings taken with the current interrupted will eliminate IR drop error. However, interrupting output current for more than a few seconds at a time could result in some depolarization of the structure and readings that are in error. Unlike the situation when a galvanic anode system is involved, a current interrupter is more essential when performing these tests on an ICCP system. A typical interruption cycle is 7 seconds on and 3 seconds off, but other long-on, short-off cycles may be used. The rectifier must be shut off while connecting an interrupter in the circuit. Where multiple rectifiers are connected to a long pipeline or similar structure, it may be necessary to interrupt multiple rectifiers simultaneously in order to obtain IR-free readings. As in the case of a sacrificial anode system, any other currents flowing through the soil in the area of a reading must also be interrupted while taking potential readings; this could again include instances of cathodically protected foreign structures crossing the pipe being tested (coordinate with the foreign structure owner).

Prepared data sheet, Potential Readings (POM-501) is available for documentation.

5.4.7.4 Submit Records for Review

[Submit records for review.] The site must maintain a record of inspections, along with recommendations and actions taken in an accessible form such as CARMA. Good records can show trends before a problem develops.

Have the data sheets from the inspections reviewed by a qualified corrosion professional. Provide the reviewer with the current and previous inspection results.

5.4.7.5 Repairs and Adjustments

The reviewer may recommend adjustments to the cathodic protection system. These adjustments may be needed since soil conditions may change somewhat over time, anodes may be consumed, and the condition of the structure coating may change. The system must maintain the protection criteria described in the specific equipment SOP and generally described in this publication (see 5.2).

Appendix A - Definitions

Anode: The electrode of an electrochemical cell at which oxidation occurs. The metal that corrodes in a galvanic cell or the positive terminal of an electrolytic cell.

Cathode: The electrode of an electrochemical cell at which reduction is the principle reaction. The metal which is protected by an anode of a galvanic cell, the negative terminal of an electrolytic cell.

Cathodic Protection: A technique to reduce the corrosion rate of a metal surface by making that surface the cathode of an electrochemical cell.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Corrosion: The deterioration of a material, usually a metal, that results from a chemical or electrochemical reaction with its environment.

Corrosion Cell: Consists of an anode and a cathode, which are electrically connected for electron flow and immersed for ion flow.

Corrosion Monitoring System: Consists of bonded or welded joints for structure electrical continuity, insulating fittings at required locations where electrical isolation of a structure is desired, and test stations for electronic access to a structure to determine potentials, etc.

Current Interrupter: A device installed in the output circuit of a rectifier, which provides a means of automatically opening and closing the circuit at programmable intervals.

Electrical Resistivity: The resistance offered to the passage of current between the opposite faces of a unit cube of the material. Units are resistance times distance, such as ohm-centimeter, ohm-meter, ohm-foot, or the like.

Electrolyte: The medium (such as water and soil) through which the current (positive charge) of a corrosion cell flows (i.e., from the anode to the cathode).

Electron Flow: Flow of electrons in the external circuit; in the opposite direction to "conventional" current flow.

External Circuit: The part of a corrosion cell circuit in which electrons flow through the metal of the anode, cathode, and metallic conductor between them (the metallic part of the circuit).

Foreign Structure: Any metallic structure that is not intended to be in electrical contact with the structure requiring corrosion monitoring and/or cathodic protection.

Galvanic Anode Cathodic Protection: Reduction of corrosion of a metal in an electrolyte by galvanically coupling it to a more anodic metal. This form of cathodic protection is also sometimes called sacrificial anode cathodic protection.

Galvanic Cell: A corrosion cell in which there is an anode made of a different material than the cathode.

Galvanic Series: A list of conductive materials, especially metals and alloys, arranged according to their corrosion potentials in a given environment.

Galvanic Corrosion: Corrosion produced by a galvanic cell.

Impressed Current Cathodic Protection: Reduction of corrosion of a metal in an electrolyte by supplying dc current through an external power source and employing an impressed current anode.

Internal Circuit: The part of a corrosion cell circuit in which the current flows through the electrolyte (the solution part of the circuit).

Joint Bonds: Cables metallurgically bonded to a structure, such as a pipe, to ensure electrical continuity for cathodic protection.

Junction Box: An enclosure containing terminals from multiple anodes and/or structures, along with accessories such as calibrated shunts and variable resistors.

Local Cell Corrosion: An electrochemical cell created on a metallic surface because of a difference in potential between adjacent areas on that surface.

Mill Scale: The oxide layer formed during hot fabrication or heat treatment of metals.

Mixed Potential: A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

Native Potential: see ‘Static Potential’.

Noble Metal: A metal with a standard electrode potential more positive than that of hydrogen. Of two metals in a corrosion cell, the one with a potential more in the noble direction will be the cathode.

Polarization: Change from static or native potential as a result of current flow across electrode/electrolyte interface. Also considered difference between polarized and native potential.

Polarized Potential: Potential determined after a cathodic protection system has been energized, but immediately after cathodic protection current is interrupted. Also referred to as “instant off” potential.

Portable Voltmeter: Any portable instrument for measuring voltage drops across electrical components of potential (voltage) differences between a structure and a stable reference electrode.

Potential: In cathodic protection work, the voltage difference between a structure and a reference electrode, all in a continuous electrolyte. Also referred to as structure-to-electrolyte potential.

Rectifier: An electrical device that converts an alternating current (ac) input to a dc output. The rectifier typically includes a stepdown transformer section to reduce the incoming ac voltage, as well as a rectification section that converts current to dc, along with meters, fuses, lightning arresters, and other accessories.

Reference Electrode: An electrode having a stable and reproducible potential, which is used in the measurement of other potentials.

Shunt Resistor: A calibrated resistor placed within a circuit to determine the current flow; calibration is typically expressed in ohms or amperage per millivolt.

Static Potential: The potential of a metal, free of any polarization and with no current flowing through the electrolyte where the potential is measured; sometimes also called 'native potential'. This potential can also be determined after cathodic protection system has been de-energized for an extended time period.

Stray Current Corrosion: Corrosion resulting from current flowing through paths other than the intended circuit. Corrosion results when this current enters the electrolyte (e.g., ground return to a foreign cathodic protection system, streetcar line, railway system, etc.).

Structure: In cathodic protection work, an item that could be monitored and/or cathodically protected (e.g., buried pipeline, submerged pump column, etc.) or an item foreign to such an article (i.e., a foreign structure).

Structure-to-Electrolyte Potential: Potential of structure in electrolyte as compared to potential of reference electrode making contact with same electrolyte. Also referred to as structure-to-soil, pipe-to-soil, and fitting-to-soil potentials.

Test Station: A location for conducting tests on a protected structure, having an enclosure containing terminals of cables from the structure and from any galvanic anodes, along with accessories such as calibrated shunts and variable resistors.

Uncorrected Potential: Potential determined with cathodic protection system energized and cathodic protection current flowing. This potential is sometimes called 'protective potential' and may contain significant IR drop error.

This page intentionally left blank.

Appendix B - Coating Inspection Log Example

Coating System Inspection Log

Project Name: ______________________ Date: ______________

Asset Name/Feature: ______________________ Total Asset Surface Area: ______________

Coating Service Condition: Atmospheric / Submerged Total Defect Surface Area: ______________

Reference Location (Start Point): ______________________ Overall Grading: ______________

Location (Clock Position looking downstream)	**Defect Type**	**Surface Area (ft^2)**	**Details, Notes, & Photo Numbers**	**Recommend Action**